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PAPER

"Clicked" fluoropolymer elastomers as robust materials for potential microfluidic device applications†

Ying-Wei Yang,[a] Jens Hentschel,[a] Yi-Chun Chen,[b] Mark Lazari,[cd] Hanxiang Zeng,[a] R. Michael van Dam[bcd] and Zhibin Guan*[a]

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We report the design and synthesis of a new perfluoropolyether-based material, which has liquid-like viscosity and can be cured into a tough, highly durable elastomer when "clicked" with selected tri-pod organic small molecules. This highly fluorinated elastomer exhibits remarkable resistance to a variety of organic solvents, water, heat and even harsh acidic and basic conditions. Whereas PDMS-based microfluidic devices are commonly used for aqueous based applications, their limited chemical resistance and high swellability in many common organic solvents make it unfeasible for microfluidic applications involving organic solvents and/or harsh conditions. With excellent chemical resistance and low swellability, our newly synthesized fluoro-elastomers will hopefully provide an alternative material for organic based microfluidic devices. Furthermore, the alkyne–azide "click" chemistry employed in curing not only provides high efficiency of synthesis and ease of device fabrication, but, more importantly, produces 1,2,3-triazole linkages that are very stable against harsh acidic or basic conditions. This work has great potential to expand microfluidics to a series of novel applications especially in organic and medicinal chemistry.

1. Introduction

The precise control and manipulation of small (10^{-9} to 10^{-18} litres) amounts of fluids in channels with dimensions of tens of micrometres—microfluidics—has emerged as a distinct new field in the beginning of the 1990s and is increasingly being employed to scale down and automate laboratory procedures in the fields of chemistry and biotechnology.[1–4] The small dimensions of microchannels can reduce reagent consumption and waste production, improve the speed and accuracy of chemical or biochemical reactions, and also allow the replication of identical reactions or screening assays on a single microfluidic chip to harness parallelism and increased throughput.[5–8]

Benefiting from the great success of photolithography and related technologies in silicon microelectronics, most of the early work in microfluidic systems employed silicon and glass,[3,4,9] which with time were largely replaced by soft materials due to the limitations of hard materials. In particular, mechanical valves are difficult and expensive to fabricate in silicon/glass-based microfluidic systems,[4] and devices of high complexity have been almost impossible due to the large size (several millimetres) of these valves.[4,10] The size can be reduced by using alternative, passive valve approaches, but their operation depends greatly on the physical and chemical properties of the fluid.[11] In contrast, the fabrication and manipulation of microfluidic devices containing valves, pumps and mixers in elastomers is much easier than that in rigid materials.[1,3,4,12–15] The employment of soft elastomeric materials has allowed microfluidics to explode rapidly into a modern technology that has found many applications in ink-jet printing, nanoscale chemical reactions, drug screening, micro-analysis related to molecular biology, optics and fuel cells.[1–8,16–20]

Poly(dimethylsiloxane) (PDMS), which is optically clear, inert, non-toxic and non-flammable, has become the most common elastomeric material in fabricating microfluidic devices for applications especially in biotechnology.[2–8,12–17] PDMS possesses many attractive properties for microfluidics, such as viscoelastic mechanical properties, low Young's modulus, biocompatibility, low surface energy and outstanding gas permeability.[4,12,14] Despite these advantages, PDMS is limited to applications mostly involving aqueous solutions. Glass and silicon microfluidic devices are still preferable to PDMS devices in many areas of microfluidic chemical synthesis and analysis, where acids, bases, and organic solvents are frequently used. This stems from the serious drawback that PDMS can dissolve or swell in many

[a]Department of Chemistry, University of California, 1102 Natural Sciences 2, Irvine, CA, 92697-2025, USA. E-mail: zguan@uci.edu
[b]Crump Institute for Molecular Imaging, University of California, Los Angeles, CA, 90095, USA
[c]Department of Molecular and Medical Pharmacology, University of California, Los Angeles, CA, 90095, USA
[d]Biomedical Engineering Interdepartmental Program, University of California, Los Angeles, CA, 90095, USA
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such solvents,[21] which makes it impossible for organic solvents and harsh aqueous solutions to flow inside the micro-scale channels. Therefore, these applications will need to revert to the early generation systems using rigid inert materials, such as glass, silicon, ceramics and metals, which are limited by the disadvantages mentioned earlier.[21]

To address this issue, DeSimone and Quake research groups reported together an organic solvent-compatible microfluidic device based on a photocurable perfluoropolyether (PFPE) elastomer.[22] This highly fluorinated elastomer exhibits a number of attractive properties, including low surface energy, high elasticity, high gas permeability, low toxicity, high chemical resistance,[22,23] and low swellability in common organic solvents.[22] This important work demonstrates the potential of extending the use of microfluidic devices to a wide variety of new chemical applications and other domains. Nevertheless, the ester and carbamate linkages involved in this elastomer system are susceptible to cleavage under basic conditions, limiting their general application for microfluidic devices used for chemical reactions. To address this critical issue, herein we report a new design of PFPE-based elastomers cured by efficient "click chemistry" that forms chemically stable 1,2,3-triazole linkages.

A critical design principle in our system is to avoid any weak linkages that are susceptible to degradation under harsh conditions, for example, in the presence of strong bases or nucleophiles. With this in mind, chemically very stable alkyl ether linkages were employed in the functionalization of both the PFPE polymer (**1**) and the cross-linker (**2**) (Chart 1). Furthermore, copper(I)-catalyzed alkyne–azide cyclization reaction, the so-called "click reaction",[24] was chosen for curing the PFPE elastomer because this reaction is highly efficient and the resulting 1,4-disubstituted 1,2,3-triazole linkages are chemically very stable. Due to many advantageous features, "click chemistry" has been extensively employed in various materials synthesis and applications.[25] Herein, we successfully employed a robust, efficient, orthogonal "click reaction" between terminal-alkyne functionalized PFPE (**1**) and tri-azide (**2**) to form a transparent elastomer suitable for microfluidic device fabrication (Chart 1). The focus of this manuscript is to report our material synthesis, characterization of their basic materials properties critical for microfluidic devices, and investigation of experimental conditions suitable for fabricating the new material for microfluidic device applications. Compared to previous elastomeric materials used for microfluidic applications, our new elastomer is more robust with excellent resistance to organic solvents, heat and base, and shows strong adhesion to glass substrates. We believe that our new elastomer technology will open a door to the fabrication of microfluidic devices for many organic-based applications.

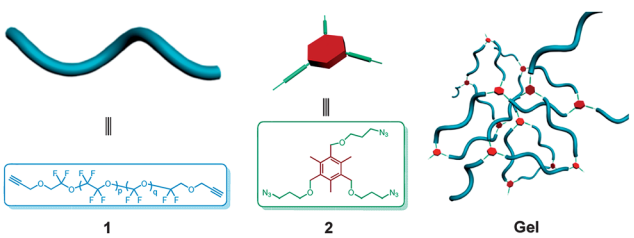


Chart 1 Structural representation of the materials used in the current study and the final gel material produced by alkyne–azide "click" chemistry.

2. Experimental section

2.1 General

^{1}H NMR, ^{13}C NMR and ^{19}F NMR spectra were recorded at 500 MHz, 125 MHz and 376 MHz, respectively on a Bruker Avance-500 Spectrometer or a Bruker ARX-400 Spectrometer. All NMR spectra are reported as δ in parts per million (ppm). ^{1}H NMR and ^{13}C NMR spectra are reported relative to residual solvent peaks. Coupling constants are reported in Hz. Electrospray mass spectrometric analysis (ESI-MS) was performed on a Micromass LCT or a Micromass Autospec Spectrometer. IR spectra were collected on a Perkin Elmer 1600 Series FT-IR spectrometer.

All reagents were used as received from commercial suppliers unless otherwise noted. Anhydrous solvents were passed through a column of activated alumina (type A2, size 12 × 32, purify) under nitrogen pressure and sparged with nitrogen before use. Deuterated solvents were purchased from Cambridge Isotope Laboratories. CD_2Cl_2 was placed over activated 4 Å molecular sieves under inert atmosphere. Flash column chromatography was performed using forced flow on EM Science 230–400 mesh silica gel.

2.2 Synthesis of starting materials

2.2.1 PFPE-dialkyne ether (1). Poly(tetrafluoroethylene oxide-*co*-difluoromethylene oxide)-α,ω-diol (Fomblin ZDOL, Aldrich, M_w 3800 M^{-1}, 3.46 g, 0.91 mmol) was dissolved in a mixed solvent of anhydrous *tert*-butanol (3.5 mL) and 1,1,2-trichlorotrifluoroethane (3.5 mL) containing potassium *tert*-butoxide (270 mg, 2.4 mmol). This solution was heated to 35–40 °C under stirring. Propargyl bromide (80 wt% solution in toluene, Aldrich, 542 mg, 0.4 mL, 3.6 mmol) was added to the reaction mixture dropwise. The reaction mixture was heated under vigorous stirring at 35–40 °C for 4 days. The solution was then cooled, filtered through Celite over a medium frit and the solvent was evaporated *in vacuo* to give a crude product, which was further purified by filtering through a 0.2 μm polyethersulfone filter to yield a clear, colorless, viscous oil (yield: 95%). ^{1}H NMR (1,1,2-trichlorotrifluoroethane/$Me_2(CO)$-d_6 4 : 1): δ 4.34 (s, 4H, $OCH_2C{\equiv}CH$), 4.01 (q, 4H, CF_2CH_2O), 2.74 (s, 2H, $OCH_2C{\equiv}CH$); ^{19}F NMR (1,1,2-trichlorotrifluoroethane/$Me_2(CO)$-d_6 4 : 1): δ −52.9, −54.3, −54.5, −56.3, −78.4, −80.5, −89.6, −89.9, −91.5, −126.8, −130.4; ^{13}C{^{1}H} NMR ($CDCl_3$): δ 126.3, 126.0, 123.9, 123.6, 121.5, 121.2, 117.9, 116.8, 116.5, 116.1, 114.3, 114.0, 113.7, 75.5, 75.4, 63.3, 58.6.

2.2.2 3-Azidopropan-1-ol. 3-Bromo-1-propanol (10 g, 6.3 mL, 72 mmol) and sodium azide (7.8 g, 120 mmol) were dissolved in a mixture of acetone (120 mL) and water (20 mL) and the resulting solution was heated to reflux overnight. After removing acetone under reduced pressure, 80 mL of water were added and the mixture was extracted with diethyl ether (4 × 80 mL). The organic layers collected were dried over $MgSO_4$ and the solvent was removed under reduced pressure to give a product as colorless oil (yield: 5.82 g, 80%). ^{1}H NMR ($CDCl_3$): δ 3.77 (q, 2H,

J = 5.8 Hz, CH_2–OH), 3.47 (t, 2H, J = 6.5 Hz, CH_2–N_3), 1.85 (quint, 2H, J = 6.0 Hz, $CH_2CH_2CH_2$), 1.53 (t, 1H, J = 5.0 Hz, CH_2OH).

2.2.3 1,3,5-Tris((3-azidopropoxy)methyl)-2,4,6-trimethylbenzene (2). 1,3,5-Tris(bromomethyl)-2,4,6-trimethylbenzene (5.8 g, 14.4 mmol) and sodium hydride (60% suspension in mineral oil, 3.4 g, 86.4 mmol) were placed in a 300 mL round bottom flask. Under a nitrogen atmosphere, THF (dry, 150 mL) was added at room temperature. At 0 °C, a solution of 3-azido-1-propanol (5.82 g, 57.6 mmol) in 15 mL THF was added dropwise. After complete addition, the mixture was allowed to warm to room temperature and was stirred for further 8 hours. Aqueous ammonium chloride solution (100 mL, 1 M) was then added in order to remove any residual hydride, which was followed by extractions with diethyl ether (4 × 120 mL). The organics were dried over $MgSO_4$. After removal of the solvent under vacuum, the product was isolated as colorless oil *via* flash column chromatography (1 : 5 EtOAc/Hexanes) (yield: 5.95 g, 89.0%). ^{1}H NMR ($CDCl_3$): δ 4.55 (s, 6H, Ph(CH_2O–)$_3$), 3.60 (t, 6H, J = 6.0 Hz, (OCH_2)$_3$), 3.40 (t, 6H, J = 6.5 Hz, (CH_2N_3)$_3$), 2.42 (s, 9H, Ph(CH_3)$_3$), 1.87 (quint, 6H, ($CH_2CH_2CH_2$)$_3$); ^{13}C{^{1}H} NMR ($CDCl_3$): δ 138.3, 132.9, 68.0, 67.1, 48.8, 29.6, 15.9. ESI-MS (CH_2Cl_2/MeOH), m/z 482.26 [M + Na]$^+$ (found); 482.26 [M + Na]$^+$ (calc).

2.2.4 1,4-Tris((3-azidopropoxy)methyl)-benzene (2a). α,α'-Dibromo-*p*-xylene (1.32 g, 5 mmol) and sodium hydride (60% suspension in mineral oil, 0.52 g, 13 mmol) were placed in a 250 mL round bottom flask. Under a nitrogen atmosphere, THF (dry, 50 mL) was added to the reaction mixture at room temperature. At 0 °C, a solution of 3-azido-1-propanol (1.32 g, 13 mmol) in 5 mL THF was added dropwise. After complete addition, the mixture was allowed to warm to room temperature and was stirred for further 8 hours. Aqueous ammonium chloride solution (30 mL, 1 M) was then added in order to remove residual hydride, which was followed by extractions with diethyl ether (4 × 30 mL). The organics were dried over $MgSO_4$. After removal of the solvent under vacuum, the product was isolated as colorless oil *via* flash column chromatography (1 : 2 CH_2Cl_2/Hexanes) (yield: 0.95 g, 62.5%). ^{1}H NMR ($CDCl_3$): δ 7.33 (s, 4H, *aryl*), 4.52 (s, 4H, Ph(CH_2O–)$_2$), 3.56 (t, 4H, J = 6.0 Hz, (OCH_2)$_2$), 3.43 (t, 4H, J = 6.5 Hz, (CH_2N_3)$_2$), 1.89 (quint, 4H, ($CH_2CH_2CH_2$)$_2$); ^{13}C{^{1}H} NMR ($CDCl_3$): δ 137.9, 128.0, 73.1, 67.1, 48.7, 29.5; ESI-MS m/z 327.15 [M + Na]$^+$ (found); 327.15 [M + Na]$^+$ (calc).

2.3 Synthesis of elastomers

To a 10 mL vial were added tri-azide **2** (38.3 mg), PFPE-dialkyne ether **1** (498.9 mg) in 0.55 mL of the mixed 1,1,2-trichlorotrifluoroethane and trifluorotoluene (v/v 6 : 1). Copper wire pieces or copper turnings (1 gram) were added to the reaction solution. The mixture was stirred for *ca.* 15 hours until the solution became viscous enough for casting. Then, the reaction mixture was transferred into a PDMS mold containing cylindrical cavities (approx. 5 mm diameter, 5 mm deep), and allowed to air-dry after 4 hours. Curing was performed in an oven at 50 °C for four hours. The PDMS mold was destroyed and cylinders of the gel removed, which are suitable for solvent-resistant and bonding strength tests.

2.4 Characterization of properties of the elastomeric materials

2.4.1 Chemical stability and solvent resistance. For the chemical stability and solvent resistance study, the general procedure was as follows. The elastomeric cylinder material was immersed in a sealed container of solvent or solution. The dry weight was taken after a period of time with or without heating. The color change of the material and material properties, such as elasticity and brittleness, as well as appearance of the solution were checked by naked eyes.

2.4.2 Surface bonding. Two bonding methods were compared for the bonding strength test. (1) One cylindrical sample of the material was attached to a second cylinder with a gas-flow hole punched through the middle. Pressure was applied to make a tight contact between surfaces, and finally the assembly was baked at 50 °C to form covalent bonding (Fig. 1b–d). (2) Freshly prepared polymer syrup was poured on a glass slide, and made into a thin film by spreading or spin-coating to act as a "glue" layer. A gas-flow hole was punched through a cylinder of the polymer, which was attached to the glass slide coated with glue, and baked at 50 °C to form strong covalent bonding. The interfacial bonding strength was tested by applying increasing pressure of nitrogen to the gas-flow hole and evaluating the highest pressure that could be applied in a cyclic on/off fashion for over 2 minutes without bond failure. Pulsing the pressure is a more stringent test (*i.e.* leads to earlier failure) than continuous pressure.

2.4.3 Thermogravimetric analysis (TGA). TGA was performed on a TA Instruments Q500. Samples (~5 mg) were equilibrated at 105 °C before ramping up to 800 °C at a rate of 20 °C min^{-1}. The experiments were carried out in air.

2.4.4 Mechanical characterization. Films for mechanical testing were prepared in the similar manner as described in the Synthesis section. The reaction solutions were cast into Teflon molds, dried for 4 hours at room temperature and 16 hours at 40 °C under vacuum.

Instron tensile tests. Standard stress/strain experiments were performed using an Instron 3365 machine. The specimens were stamped out from solution cast films and extended at 50 mm min^{-1} at room temperature. The measurement was repeated three times. Young's modulus (E) was determined from the initial stress–strain slope.

Dynamic mechanical analysis (DMA). DMA was carried out on a TA Instruments Q800 using a standard temperature sweep experiment between −80 and 80 °C. Samples were cut into 6 mm × 3 mm × 0.5 mm (length × width × thickness) rectangles. The initial force was 10 mN, and the heating rate was 3 °C min^{-1} at a constant frequency of 3.2 Hz. The glass transition temperature (T_g) was determined at the peak maximum of the tan δ signal.

Rheometry. The storage modulus (G') and loss modulus (G'') of the final cross-linked polymer material were determined at

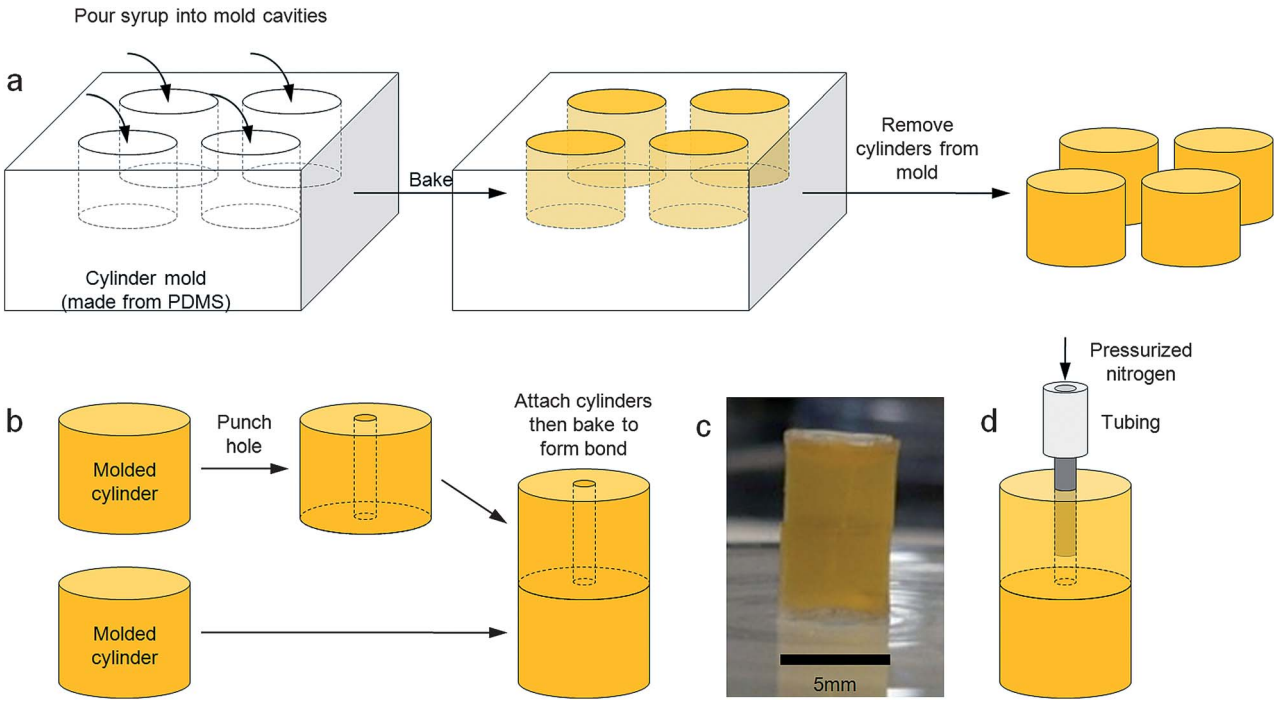


Fig. 1 (a) Casting of syrup in PDMS mold to make polymer cylinders for testing. (b) Fabrication of bond strength testing devices from molded cylinders of polymerized syrup. (c) Photograph of the finished structure. (d) Pressurized nitrogen is supplied *via* the gas-flow hole to the bonding interface.

25 °C and at different frequencies (0.01–100 Hz) in standard frequency sweep measurements (0.1% strain, 5 N normal force) using an AR G2 Rheometer from TA Instruments (12 mm steel plate).

3. Results and discussion

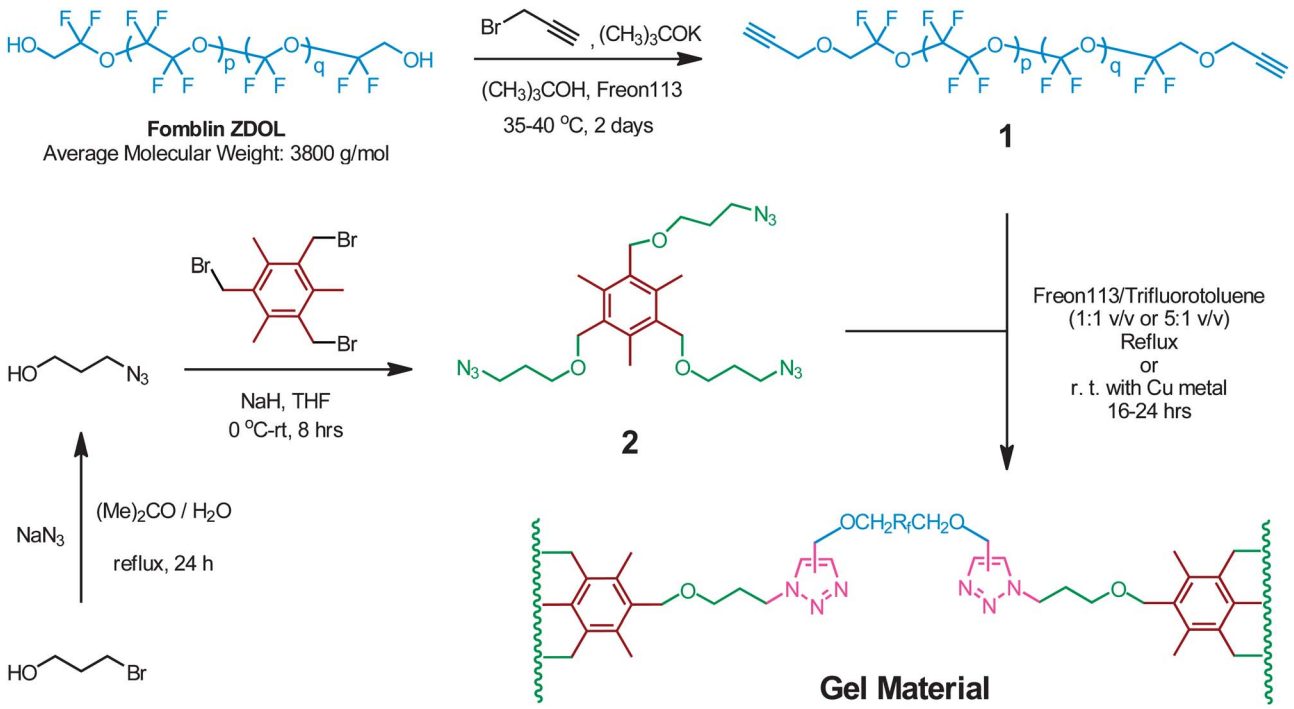
3.1 Material synthesis

As shown in Scheme 1, the ZDOL potassium dialkoxide solution was prepared directly by simply dissolving it in an equivolumetric mixture of anhydrous *tert*-butanol and 1,1,2-trichlorotrifluoroethane (final concentration 0.5 g mL^{-1}) containing a slightly excess amount of potassium *tert*-butoxide. Given the significantly more acidic terminal alcohol on ZDOL PFPE diol ($pK_a \approx 12.5$ in H_2O) as compared to *tert*-butanol ($pK_a \approx 17$ in H_2O), the PFPE diol should be quantitatively converted to its potassium dialkoxide. The temperature was raised to 35–40 °C, and an excess amount of propargyl bromide in toluene (3–4 mol per mol of ZDOL) was added dropwise. Etherification at both termini of PFPE diol *via* S_N2 substitution resulted in the formation of PFPE-dialkyne, **1**. ^{19}F NMR and ^{1}H NMR analyses of the product showed a conversion of the etherification reaction to be more than 95%. The use of a mixed solvent of anhydrous *tert*-butanol and 1,1,2-trichlorotrifluoroethane (Freon 113) is necessary because of the difficulty of dissolving ZDOL of this molecular weight (M_n around 3800) in pure *tert*-butanol. Etherification of ZDOL with propargyl bromide was highly efficient even at low temperature owing to the high reactivity of propargyl halides. The ^{1}H NMR and ^{13}C NMR spectra confirmed the quantitative conversion of terminal hydroxyl into alkyne for the PFPE diol. In the ^{19}F NMR spectrum of the final product **1**, the signals from −52.9 to −56.3 ppm and −89.6 to −91.5 correspond to the backbone repeat units of PFPE. The end group region extends from −78.4 to −80.5 ppm. The amount of "free" (not etherified) $–CF_2CH_2OH$ groups on the crude oligomer can be evaluated by comparing the integral of signals at −81.4 (and −83.5) ppm with those at −78.4 (and −80.5) ppm (etherified). The free alcohol end is less than 5%, which is sufficient for device fabrication. Further evidence of this substitution was the appearance of a strong peak at 3325 cm^{-1} in FT-IR spectroscopy, corresponding to the $–C{\equiv}C–H$ stretching.

Many practical difficulties were met in the cross-linking polymerization reaction shown in Scheme 1, mainly due to the poor miscibility of the product in the solvent mixture. Under an optimized reaction condition, we successfully "clicked" polymerized PFPE-dialkyne **1** and tri-azide **2** to form a crosslinked network. The FT-IR spectrum of the polymerization product shows the appearance of a new peak at 1631 cm^{-1} corresponding to the newly formed triazole ring as well as the disappearance of the peak at 2102 cm^{-1} corresponding to the azide group. A control experiment using a di-azide **2a**, 1,4-tris((3-azidopropoxy) methyl)-benzene, instead of tri-azide **2**, for the click reaction did not produce any gel material, indicating no crosslinking of the difunctional monomers.

3.2 Investigation of material fabrication conditions

Initially, the fabrication condition with our new material was investigated without using any copper catalyst. In classical Huisgen reaction, 1,3-dipolar cycloaddition between a terminal alkyne and an organic azide occurs at elevated temperature



Scheme 1 Synthesis of starting materials and the final elastomer.

without any catalyst.[25] Therefore, PFPE-dialkyne **1** and tri-azide **2** were dissolved in a minimum amount of mixed Freon 113 and trifluorotoluene (1 : 1) in a round bottom flask and the resulting homogeneous solution was then heated at reflux under stirring overnight until the solution became much more viscous. The reason for employing a mixed solvent is to avoid phase separation. Then the reaction mixture was transferred to a small vial, which was heated slowly from 80 °C to 130 °C to prevent porosity due to fast evaporation of solvent. No phase separation was observed during the reaction. After several hours, the gel formed after all the solvents were removed. This gel material is suitable for further solvent-resistant tests.

However, this procedure for casting the gel is complicated by the need for a complex temperature profile that depends on somewhat subjective evaluations of viscosity. The ideal reaction condition would be simply mixing the starting materials together and then casting them into a mold.

Toward this goal, the first optimization of gel fabrication is to remove this complex heating profile. Without heating, the click reaction is significantly slowed down, which requires the use of an appropriate catalyst to accelerate the click reaction. A preliminary screening of various copper(I) salts as potential catalysts did not offer us any good results, presumably due to the insolubility of those salts in the reaction mixture. Furthermore, removal of the catalyst after the reaction is also an issue. On the other hand, the use of copper metal, copper turnings and copper wires at room temperature resulted in significant acceleration of the reaction. The removal of copper metal is extremely easy because it settles at the bottom of the reaction container prior to casting.

In further optimization of material fabrication conditions, we aimed at minimizing the amount of solvents used in the reaction, especially trifluorotoluene, which is difficult to remove during the device fabrication. The presence of solvents can interfere with microfluidic device fabrication by the formation of solvent vapor bubbles that disrupt the contact between PFPE surfaces during the bonding process. However, bulk polymerization without any solvent did not proceed well because the two starting materials, *i.e.*, PFPE-dialkyne (**1**) and tri-azide (**2**), are immiscible. Therefore, the optimal condition is to use a minimal amount of Freon 113/trifluorotoluene mixed solvents to dissolve both starting materials, and then stir the reaction mixture overnight in the presence of an appropriate amount of copper metal as the catalyst (see the Experimental part for the detailed reaction conditions). It is critical to reach an appropriate polymerization degree, as indicated by the viscosity of the polymerization solution, before casting of the material into the mold. Once the polymerization formed a syrup with suitable viscosity for casting, the reaction mixture was cast into a mold and/or spin-coated onto a substrate surface. With slow evaporation of solvents and further curing, the syrup will eventually form a robust transparent elastomer. The fabricated samples were finally cured in an oven at 50 °C to allow the complete polymerization of azide and alkyne functional groups (Fig. 1a).

3.3 Thermal stability

As reported by Whitesides *et al.*, PDMS-based microfluidic devices have limited compatibility with organic solvents.[1,21,23] In comparison, the PFPE-based elastomers prepared in this study showed a number of improved features in terms of the thermal stability, acid/base resistance and solvent resistance. The initial thermal stability test shows that the gel is very stable with no weight or color change after heating at 50 °C for 5 hours. More quantitative thermal stability analysis was conducted by thermogravimetric analysis (TGA) (Fig. S1 in the ESI†), which

shows that the material has no appreciable thermal decomposition at temperatures below 350 °C.

3.4 Solvent and chemical resistance

PDMS-based microfluidic devices have very limited compatibility with organic solvents. Here, we choose some commonly used organic solvents available in most organic labs to test the solvent resistance of our new material. The initial swelling test in DMSO at room temperature with 7 days immersion shows a weight change of less than 4%, suggesting excellent compatibility with this solvent. Screening of a series of commonly used organic solvents, such as DCM, MeCN, DMSO, DMF, H_2O, Freon 113, toluene, and trifluorotoluene, further validated that the "click" PFPE gel material is highly compatible with a variety of organic solvents (entries 1–4 in Table 1). For comparison, the PFPE gels reported previously[22a] show higher swellability, especially in fluorinated solvents such as trifluorotoluene (entry 2 in Table 1). In further tests, the "click" PFPE material exhibited an excellent chemical stability under harsh basic or acidic conditions even at elevated temperatures. Under strong acidic conditions (3 N HCl or 5 M TFA) at 120 °C, the material shows very small changes (entries 5 and 6 in Table 1). The test of material stability under basic conditions is particularly important because the previously reported PFPE material contains ester and carbamate linkages,[22a] which are presumably sensitive to basic conditions. We first tested the stability in 1 M K_2CO_3 aqueous solution at various temperatures and times. The "click" PFPE gel showed a negligible change under all the conditions. However, the previously reported PFPE showed a significant amount of suspension present in the solution after being heated at 80 °C in 1 M K_2CO_3 aqueous solution for 90 h (entry 9, Table 1). Finally, we tested the materials in a strong basic solution, namely 1 or 3 N NaOH aqueous solution, at various temperatures and times. The two types of PFPE gels showed significantly different stability to strong basic solutions. Under all NaOH test conditions (entry 11–15, Table 1), the "click" PFPE gel showed no or only slight color change, with no suspension or change in flexibility being observed. In sharp contrast, the previously reported PFPE gel showed substantial degradation under 1 or 3 N NaOH aqueous solution for prolonged heating (entries 14 and 15, Table 1), as evidenced by the turbidity and color change of the solution. After the base treatment, the material also became noticeably more flaky and weaker. These tests confirm that the "click" PFPE material shows excellent resistance to heat, organic solvents, and acidic and basic solutions. We attribute the excellent stability to the chemical design of the "click" PFPE gel: there is no weak chemical linkage in the polymer that is susceptible to chemical degradation. Both the ether linkage and the 1,2,3-triazole ring formed from "click" reaction are stable. These new design features, in combination with the inherent chemical stability and solvent resistance for PFPE, make our "click" PFPE material an excellent candidate for microfluidic device fabrication for enhanced solvent resistance and chemical/thermal stability.

3.5 Mechanical properties

The mechanical properties of the PFPE elastomer prepared by click reaction were investigated by several methods. Instron tensile tests revealed a typical rubber-like stress–strain behavior (Fig. S2 in the ESI†), with a strain at break about 175% at a stress of *ca.* 2.1 MPa. The Young's modulus (E) measured from the initial slope on the stress–strain curve was 3.5 MPa, which is

Table 1 Solvent resistance and thermal stability tests on the "click" PFPE elastomer compared to the DeSimone/Quake PFPE elastomer[b]

				"Clicked" PFPE		DeSimone/Quake PFPE[22a]	
Entry	Conditions	Temp./°C	Time/h	Weight change	Appearance change	Weight change	Appearance change
In pure organic solvents							
1	Pure solvents[a]	25	14	<±3%	No	<6%	Slightly cloudy for DMSO and toluene
2	Trifluoro-toluene	25	14	<±3%	No	+13%	No
3	MeCN	120	0.33	+1.9%	No	+1.9%	No
4	DMSO	130	0.50	+2.9%	Darker	+2.6%	No
Under acidic conditions							
5	3 N HCl	120	0.33	<1%	No	<1%	Slightly darker
6	5 M TFA	120	0.33	−3.9%	No	+1.4%	Slightly darker
Under basic conditions							
7	1 M K_2CO_3	25	10	<1%	No	<1%	No
8	1 M K_2CO_3	80	10	<1%	No	<1%	No
9	1 M K_2CO_3	80	90	<1%	Slightly yellow, no suspension	<1%	Significant suspension in solution
10	1 M K_2CO_3	120	0.33	<1%	No	<1%	No
Under strong basic conditions							
11	1 M NaOH	25	10	<1%	No	<1%	No
12	1 M NaOH	80	10	<1%	No	<1%	No
13	1 M NaOH	80	90	<1%	Slightly yellow; no suspension; no change in flexibility	<1%	Significant suspension in solution; slight flexibility change
14	3 N NaOH	80	90	<1%	Slightly yellow; no suspension; no change in flexibility	+1.62%	Darker, turbid solution; noticeably flaky and easy to break
15	1 N NaOH	120	90	−3.41%	Slightly yellow; no suspension; no change in flexibility	−6.51%	Darker, very turbid solution; weak and flaky, easy to break

[a] CH_2Cl_2, MeCN, DMSO, DMF, H_2O, and PhMe. [b] There is an uncertainty of weight measurement due to the potential loss of flaky material.

Table 2 Mechanical properties of the PFPE elastomer

	G'^a/ MPa	G''^a/ MPa	E^b/MPa	Strength at break^b/MPa	Strain at break^b (%)	$T_g{}^c$/°C
Gel	1.04	0.10	3.5 ± 0.2	2.1 ± 0.3	175 ± 30	−10

[a] Measured at 25 °C and 1 Hz. [b] Estimated from 3 stress–strain tensile experiments. [c] Determined by DMA.

similar to previously reported tensile moduli of cured PFPE and PDMS materials (3.9 MPa and 2.4 MPa, respectively).[22a] Rheometric measurement confirms the PFPE gel as a robust elastomer with a storage modulus of ~1 MPa (Fig. S3 in the ESI†). Finally dynamic mechanical analysis (DMA) reveals that the PFPE elastomer has a glass transition temperature below room temperature (−10 °C), as shown in Fig. S4 in the ESI†. The mechanical properties of the PFPE elastomer are summarized in Table 2.

3.6 Interfacial bonding strength

Valve actuation in elastomeric microfluidic devices needs a strong bond between two different layers of the material. One advantage of our material is that there are still active alkyne and azide functional groups left un-reacted on the surface. In principle, it should be possible for the material to react further at interfaces between layers with or without the use of fresh material as glue. Here, two different bonding methods were employed for the bonding strength test (see the Experimental part). Preliminary tests of bonding strength show that the simple devices made by both methods can hold pressure at the bonding interface. The second method gave a much stronger layer-to-layer bonding, capable of withstanding nitrogen pressure up to about 80 psi [550 kPa]. This is comparable to the best bond strengths achieved in PDMS devices[26] and is significantly greater than previously reported for PFPE materials.[26] The ability to sustain these pressures at the bonding interface suggests the possibility to fabricate multi-layer microfluidic devices with integrated microvalves.

4. Conclusions

In summary, we designed and synthesized a new type of robust elastomer by "click" polymerization of perfluoropolyethers (PFPEs) with tri-azide terminated organic small molecules. The alkyne–azide "click" chemistry employed in curing not only provides high efficiency of synthesis and ease of device fabrication, but, more importantly, produces 1,2,3-triazole linkages that are very stable against harsh acidic or basic conditions. These new design features, in combination with the inherent chemical stability and solvent resistance for PFPE, render the "click" PFPE material remarkable resistance to a variety of organic solvents, heat and even harsh acidic and especially basic conditions. In addition, the material also shows strong adhesion to glass and itself, an important property for device fabrication. This new material overcomes a number of disadvantages of the current materials used in microfluidic device fabrication, including PDMS and the previously reported PFPE gels. We envision that our "click" PFPE elastomer will be an excellent candidate for microfluidic applications involving organic solvents and/or harsh conditions. Further studies including microfluidic device fabrication using the "click" PFPE elastomer are currently under investigation.

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