Electronic Supplementary Information (ESI)

Far infrared-assisted embossing and bonding of poly(methyl methacrylate) microfluidic chips

Qiwen Chen, Luyan Zhang and Gang Chen *

School of Pharmacy, Fudan University, 826 Zhangheng Road, Shanghai 201203, China
E-mail address: gangchen@fudan.edu.cn; Tel: +86-21-51980061; Fax: +86-21-51980168

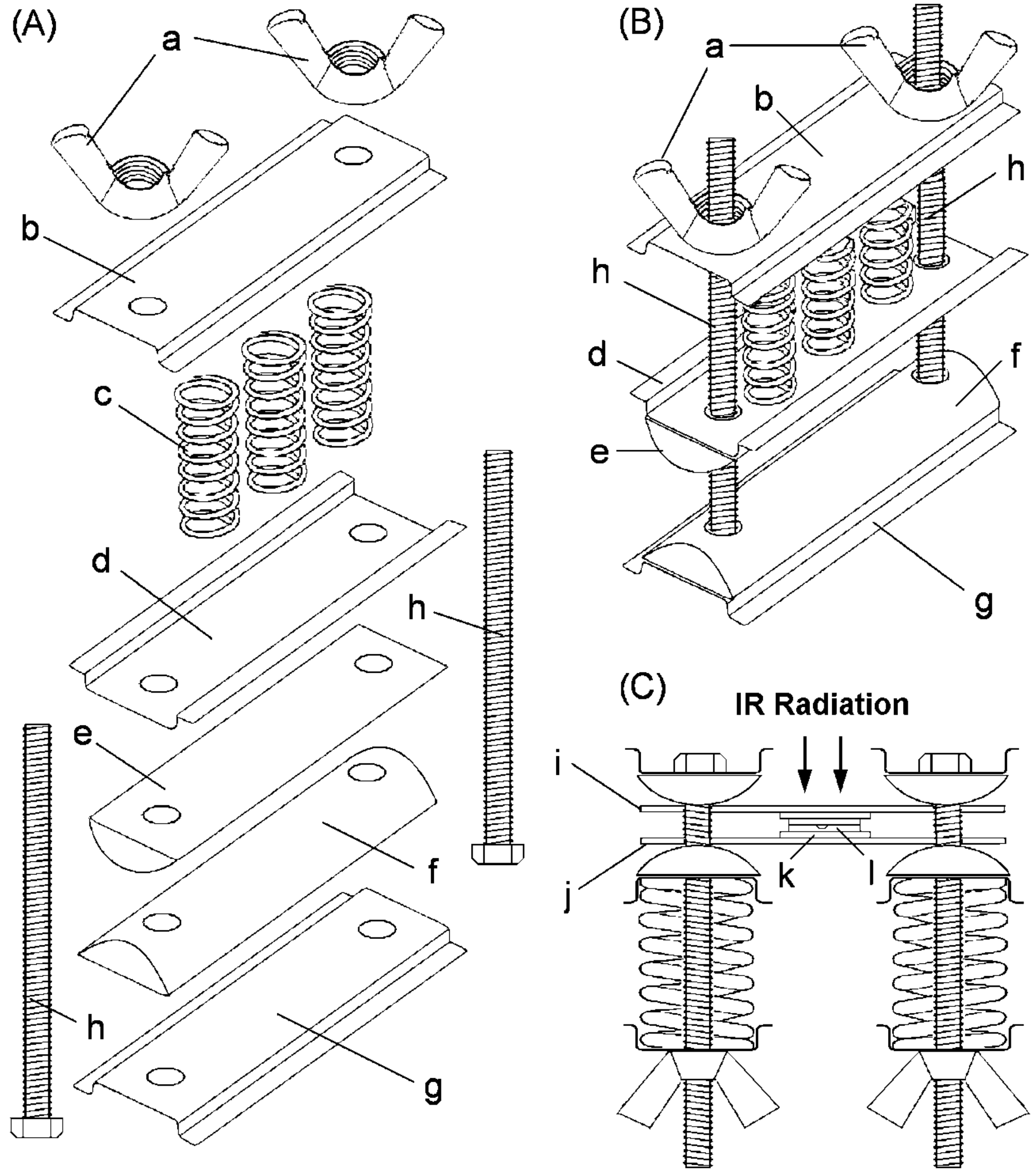

Fig. S1 Schematics illustrating a spring-driven press for hot embossing and thermal bonding of PMMA microfluidic chips (A, expanded view, B, oblique view) and (C) the side view of an assembled press system. (a) Buffer nut, (b) upper clamping plate, (c) compression spring, (d) middle clamping plate, (e) upper silicone rubber press head, (f) lower silicone rubber press head, (g) lower clamping plate, (h) screw bolt, (i) upper glass press pad, (j) lower glass press pad, (k) microscopic glass slide, (l) template and PMMA plate during hot embossing (or PMMA channel plate and PMMA cover plate during thermal bonding).

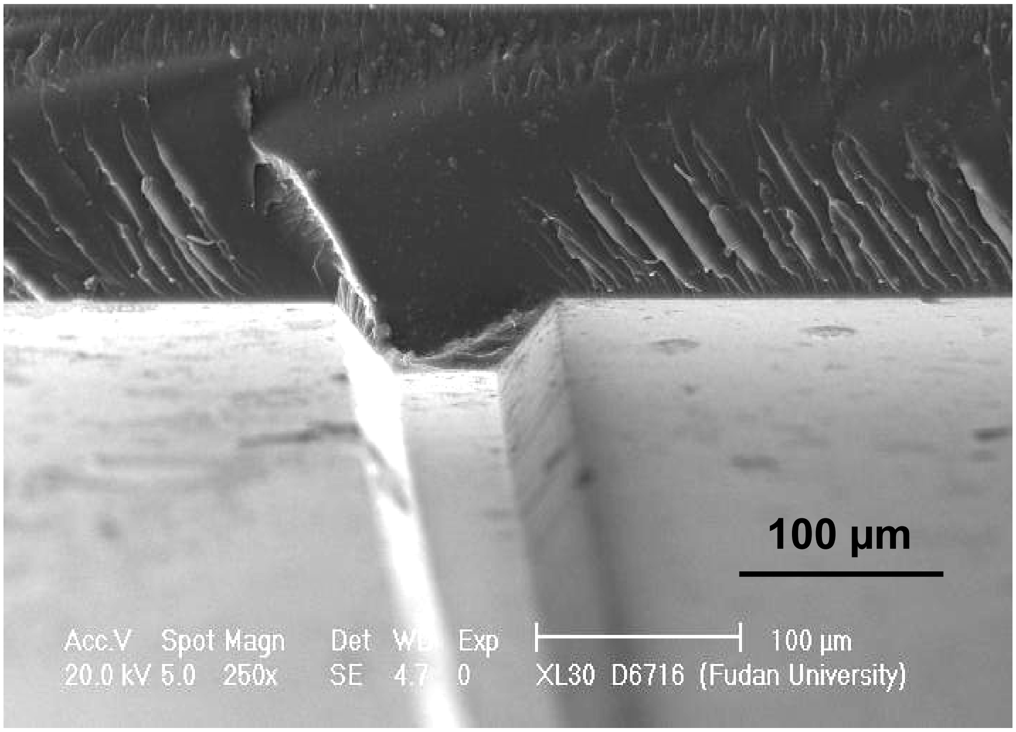

Fig. S2 SEM image showing the cross sections of the channel ridge structure on an epoxy template.

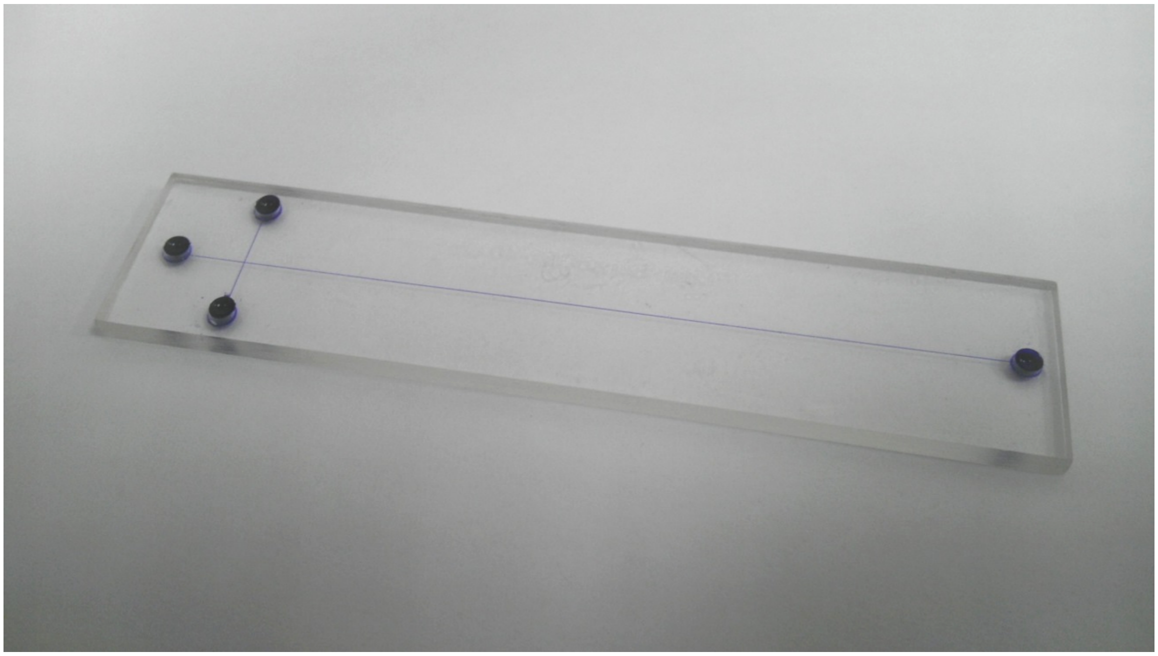

Fig. S3 Photograph of a PMMA microfluidic chip with channels filled by blue ink.

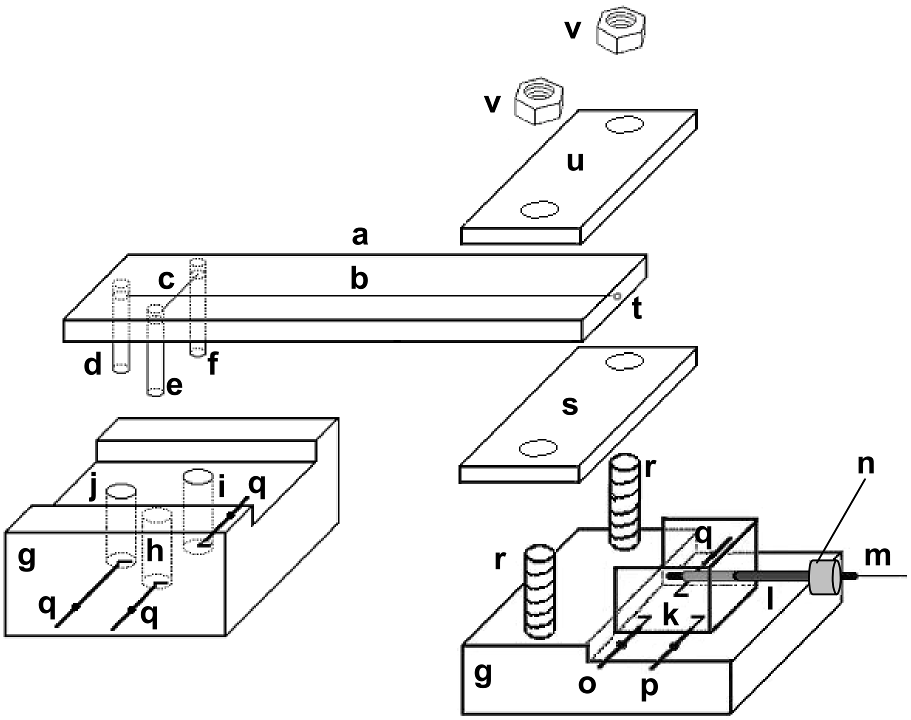

Fig. S4 Schematic showing a 3D adjustable device for the amperometric detection of microchip electrophoresis. (a) PMMA microchip, (b) separation channel, (c) injection channel, (d) pipette tip for buffer reservoir, (e) pipette tip for reservoir not used, (f) pipette tip for sample reservoir, (g) Plexiglas holder, (h) buffer reservoir not used, (i) sample reservoir, (j) buffer reservoir, (k) detection reservoir, (l) stainless-steel guiding tube, (m) capillary-based disc detection electrode, (n) silicon rubber holder, (o) auxiliary electrode, (p) Ag/AgCl reference electrode, (q) high voltage power electrode, (r) screw bolt, (s) silicon rubber sheet, (t) channel outlet, (u) Plexiglas cover plate, (v) screw nut. Dimensions are not in scale.

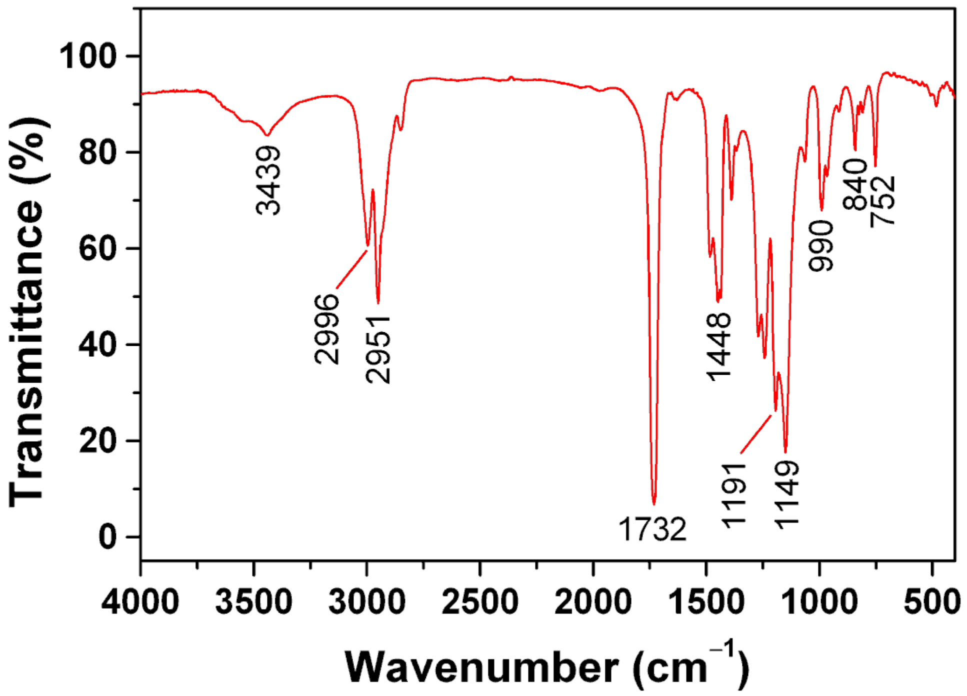

Fig. S5 Fourier transform infrared (FT-IR) spectrum of PMMA.

Experimental section

1. Reagent and solutions

Sodium dodecylsulfate (SDS), borax, nitrobenzene (NB), 2,4-dinitrotoluene (DNT), p-nitrobenzene (PNT), methyl methacrylate (MMA), benzoin ethyl ether (BEE), and 2,2'-azobisisobutyronitrile (AIBN) were all purchased from SinoPharm (Shanghai, China). Prior to use, the MMA need to be washed with 5% NaOH aqueous solution to remove the polymerization inhibitor and distilled under vacuum. AIBN was purified by recrystallization using hot methanol. Bisphenol-A-based epoxy resin and hardener were obtained from Shanghai Resin Factory (Shanghai, China). The stock solution (1000 ppm in acetonitrile) of 2,4,6-trinitrotoluene (TNT) was obtained from Radian International (Austin, TX, USA). Graphite powder was supplied by Aldrich (Wilwaukee, WI, USA).

The electrophoretic separation medium was 15 mM borax-15 mM SDS (pH 9.2). Stocking solutions (2000 ppm) of NB, DNT, and PNT were all prepared in absolute ethanol and diluted to the desired concentration with the electrophoretic separation medium solution just prior to use.

2. Manufacturing of spring-driven press

Fig. S1 illustrates the schematics of the spring-driven press for hot embossing and thermal bonding of PMMA microfluidic chips. This simple clamping device consisted of two semi-cylinder silicone rubber press heads (e and f, 25 mm diameter, 100 mm long), three iron clamping plates (b, d and g, 35 mm × 100 mm × 5 mm, the thickness of the steel plate, 1.2 mm), and three compression springs (c, 22 mm outer diameter, 56 mm height; spring constant for each spring, ~1 kg mm^{-1}) (Fig. S1A). The clamping plates was prepared by cutting a mounting rail (35 × 1000 mm) for mounting a plurality of uniform electrical connectors into 100-mm long pieces using a hacksaw. The semi-cylinder press heads were made of silicone rubber rods (25 mm diameter). As illustrated in Fig. S1B, they were assembled together using two screw bolts (h, 6 mm diameter, 100 mm long) and two butterfly nuts (a, inner diameter, 6 mm) via the holes at their ends. All parts of the press device are commercially available. The upper press head as well as the upper and the middle clamping plates are movable. The holes beside both ends of the elastic press heads (e and f) were made using a punch. Their diameter (5 mm) was small than that of the screw bolts (h) so that the press heads could not move without the aid of external force. The distance between the two screw bolts (h) was 80 mm. The photographs of spring-driven presses are illustrated in Fig. 1A and 1B.

Fig. S1C illustrates the side view of an assembled press system for far IR-assisted embossing and bonding. It consists of two spring-driven press devices and two glass press pads (i and j, 120 × 78 × 3 mm). After the aligned epoxy template and PMMA plate for hot embossing (l, or the aligned PMMA channel plate and PMMA cover plate for thermal bonding) were sandwiched by two microscopic glass slides (k, 76.2 × 25.4 × 1 mm), they were clamped between the upper and lower press pads (i and j). Each short edge side of the aligned press pads was then assembled between the two elastic press heads (e and f) of a press device by fastening the screw nuts (a) on the upper clamping plate (b). Upon fastening the screw nuts (a), the springs (c) would drive the middle clamping plate (d) and the upper press head (e) to move towards the lower press head (f). When the upper press head touched the lower press pad (j), the springs were compressed to generate force that could be adjusted by fastening and loosening the screw nuts (a). Because the six compressed springs (c) were parallelly assembled, the generated force (F (kg)) could be estimated based on the number of the spring ($n = 6$), the spring constant (k = ~1.1 kg mm^{-1}) as well as the length difference between the free and the compressed springs (x (mm)) by using Hooke's law ($F = nkx$). The maximum press force of each spring-driven press device was approximately 100 kg. The pressure (P (kg cm^{-2})) applied on the parts of the microfluidic chips and the template was calculated based on the applied force (F (kg)) and their area (S (cm^2)).

3. Fabrication of epoxy template

The epoxy templates used in this work was replicated from negative PMMA templates that were fabricated by in situ polymerization on silicon templates. Simple-cross microfluidic chip (Fig. 3c) was designed and fabricated in this work. Photolithographic negative mask designed using software (Adobe Illustrator CS3, Adobe) was transferred onto a PET transparency film at a local photo shop using a high-resolution printer at a resolution of 3600 dpi. It consisted of a 65-mm-long separation channel and a 10-mm-long injection channel that crossed each other at the middle point of the injection channel while the distance between one end of the separation channel and the injection cross was 5 mm. The channel network consisted of 50 μm wide black lines on a transparent background. Silicon wafers (p-type, 500 mm thick, 4-inch diameter, with a <100> orientation, Wafer Works, Shanghai, China) were used to fabricate template bearing positive relief of the channel network using standard photolithography and wet etching.[ESI-1] The raised channels on the template had a trapezoidal cross section with a top width of ~112 μm, bottom width of ~50 μm, and depth of ~38 μm.

To fabricate negative PMMA template, methyl methacrylate containing BEE (0.2% w/v, a UV initiator) and AIBN (0.2% w/v, a thermal initiator) was allowed to prepolymerize in an 85 °C water bath for 15 min to generate a dense prepolymer molding solution. After 1.5 mL of the molding solution was cast directly on the positive silicon template along the raised separation channel, a piece of PMMA plate (75 × 16 × 1 mm) was covered on it and pressed slightly until that all the interspaces were filled by the molding solution. Subsequently, the sandwiched molding solution was exposed to UV light (365 nm lamp, 20 W, Shanghai Jinguan Lamp, Shanghai, China) through the PMMA plate for 30 min at 25 °C to complete polymerization. Demolding of the negative PMMA template was carried out by sonicating the mold in a 40 °C water bath for 10 min.

To prepare epoxy template, bisphenol-A-based epoxy resin and hardener (Shanghai

Resin Factory, Shanghai, China) were mixed thoroughly at a weight ratio of 2:1 and degassed under vacuum. After 2.0 mL of the dense mixture was cast on a negative PMMA template, a frosted glass plate (76.2 × 25.4 × 1.2 mm) was pressed on it slightly so that a layer of epoxy resin solution formed in the interspaces between them. The thickness of the epoxy template was defined to be ~150 μm by using a spacer sandwiched between the frosted glass plate and the support under the PMMA template. The sandwiched hardener-containing epoxy resin was allowed to cure at 25 °C for at least 3 h. Finally, the PMMA template was separated from the epoxy layer to obtain a hard epoxy template adhered on the frosted glass plate. The epoxy template could be easily replicated from the negative PMMA template bearing negative relief of channel networks and could be mass-produced. Fig. S2 illustrates the cross sections of the channel ridge structure on an epoxy template.

4. Electrode fabrication

A piece of copper wire (10 cm long, 150 μm diameter) was inserted into a 3.0 cm long fused silica capillary (320 μm I.D. × 450 μm O.D., Hebei Yongnian Ruipu Chromatogram Equipment Co., Ltd., Hebei, China) and a 2 mm opening was left in the capillary for the subsequent filling of the graphite-epoxy composite. The other end of the capillary was sealed together with copper wire by thermal adhesive. Epoxy resin and hardener was mixed thoroughly at a weight ratio of 2:1. The graphite powder and the mixture of epoxy resin and hardener were hand-mixed at a ratio of 1:1 (w/w). The graphite-epoxy composite was subsequently packed into the capillary by pressing the opening end of the capillary (to a depth of ~3 mm) into a sample of the composite. The graphite-epoxy composite should touch the end of the copper wire inside the capillary tightly for the electric contact. The composite was then allowed to cure at room temperature for at least 3 h.

5. Fabrication of 3D adjustable devices for the amperometric detection (AD) of

microchip electrophoresis

Details of the 3D adjustable device for the AD of microchip electrophoresis were illustrated in Fig. S4. Plexiglas holders (g) were fabricated for housing the PMMA microchip (a) and the detection reservoir (k) allowing their convenient replacement and reproducible positioning, with silicone grease providing proper sealing. A three-electrode AD system was fabricated in the detection reservoir (at the channel outlet side, see Fig. S4) and consisted of a platinum wire auxiliary electrode (o), an Ag/AgCl wire reference electrode (p), and a 320 µm diameter graphite-epoxy composite detection electrode (m) fabricated in this work. The detection electrode (m) was placed opposite the channel outlet (t) through the stainless-steel guiding tube (l, 500 µm I.D. × 800 µm O.D.). Short pipette tips (d–f) were inserted into each of the three holes on the PMMA microchip for solution contact between the channel on the chip and the corresponding reservoir (h–j) on the left chip holder in Fig. S4. Platinum wires (q) inserted in the individual reservoirs (h–k) served as contacts to the high-voltage power supply. The end of the guiding tube (l) outside the detection reservoir (k) was sealed by a piece of small silicon-rubber holder (n, 3 mm diameter, 2.5 mm thick) with the capillary-based detection electrode (m) inserted inside. The silicon rubber holder (n) could not only prevent solutions in the detection reservoir (k) from leaking, but also hold the detection electrode (m) while allowing the detection electrode to move back and forth to define a desired gap distance to the channel outlet (t).

The distance (20 mm) between the two screw bolts (r) on the right Plexiglas holder in Fig. 4 is wider than the width of the microchip (a, 16 mm), allowing the microchip (a) to move right and left slightly to accomplish a satisfactory alignment with the detection electrode. A piece of 2.5 mm thick high-elasticity silicon rubber sheet (s) was attached to the bottom of the microchip and subsequently sandwiched between a Plexyglas cover plate (u) and the Plexiglas holder (g) with the aid of the screw bolts (r) and screw nut (v), allowing it to be adjusted up and down within 1 mm to align the channel outlet to the detection electrode. With the aids of the 2D adjustable microchip (a) and the 1D adjustable disc detection electrode (m), the present microchip electrophoresis-AD system shown in Fig. S4 facilitates the 3D alignment between the channel outlet and the detection electrode (m) without need of a complicated three-dimensional manipulator.

6. Apparatus

Scanning electron micrography (SEM) images of the microchannels were acquired with a PHILIPS XL 30 scanning electron microscope (Netherlands). The FT-IR spectrum of PMMA was measured using a FT-IR spectrometer (NEXUS470, NICOLET).

The microchip electrophoresis-AD system has been described previously.[ESI-2] A homemade high-voltage power supply with output voltage in the range of 0 and +4000 V was employed for the electrophoretic separation and the electrokinetic sample introduction. The PMMA microchips (Fig. 3c, 75 × 16 × 2 mm) were fabricated in this work. It consisted of a four-way injection cross with 65 mm long separation channel and side arms of 5 mm long each. The original waste reservoir was cut off to leave the channel outlet exposed at the end side of the chip for AD. In this work, the effective length of the separation channel (from the injection cross to the detection point) was 60 mm. The channels in the chips had a trapezoidal cross section with a top width of ~110 μm, bottom width of ~50 μm, and depth of ~37 μm.

7. End-column AD

Before use, the detection electrode was polished with emery paper, rinsed with doubly distilled water, and finally the surface of the detection electrode (Fig. S4m) was positioned carefully opposite the outlet (Fig. S4t) of the separation channel via the guiding tube (Fig. S4l). The gap distance between the detection electrode and the channel outlet was adjusted to ~50 μm by comparison with the bottom width of the channel (~50 μm) while being viewed under a microscope. An electrochemical analyzer

(CHI 830B, Shanghai Chen-Hua Instruments Co., Ltd., Shanghai, China) was used to provide a constant potential of −0.65 V (*vs.* Ag/AgCl) to the detection electrode and measure the output current in combination with a three-electrode electrochemical cell consisting of a graphite-epoxy composite detection electrode (Fig. S4m), an auxiliary electrode (Fig. S4o) and an Ag/AgCl wire reference electrode (Fig. S4p).

8. Electrophoretic procedure

Prior to use, the channels in the PMMA chip were rinsed with 0.1 M NaOH aqueous solution and doubly distilled water for 10 min each. The running buffer (Fig. S4j) and unused (Fig. S4h) reservoirs were filled with electrophoretic separation medium solution, while the sample reservoir (Fig. S4i) was filled with a mixture of NB, DNT, TNT, and PNT in the electrophoretic separation medium. The detection reservoir (Fig. S4k) was filled with the electrophoretic separation solution. In this work, floated injection was employed to introduce the sample solution into the separation channel (Fig. S4b). A voltage of +2000 V was applied to the sample reservoir (Fig. S4i) for 20 s to facilitate the filling of the injection channel (Fig. S4c), while the detection reservoir (Fig. S4k) was grounded and all the other reservoirs floating. The sample solution was loaded into the separation channel by applying +2000 V to the sample reservoir (Fig. S4i) for 1 s, while the detection reservoir (Fig. S4k) grounded and other reservoirs floating. The separation was performed by applying +2000 V to the run buffer reservoir (Fig. S4j) with the detection reservoir grounded and other reservoirs floating.

9 References in ESI

[1] Y. Chen, H. T. Duan, L. Y. Zhang and G. Chen, *Electrophoresis*, 2008, 29, 4922.

[2] B. G. Wei, L. Y. Zhang and G. Chen, *New J. Chem.*, 2010, 3, 453.