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Parallel Ionic Liquid Semi-Packed Microfabricated Columns for Complex Gas Analysis

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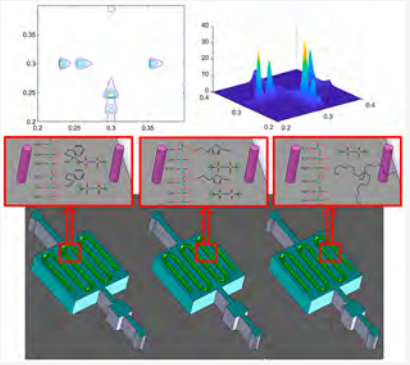
ABSTRACT: The paper presents a parallel micro gas chromatography approach using three ionic liquid semipacked columns. Switching from single column to multiple parallel columns with different selectivity enhances the power of compound identification without increasing the analysis time. The columns are fabricated using microelectromechanical systems (MEMS) technology containing an array of microfabricated pillars. The columns are 1 m-long and 240 μm-deep with four pillars per row. All columns were functionalized with ionic liquid stationary phases using a modified static coating technique and demonstrated the number of theoretical plates between 5000 and 8300 per meter. The chip performance was investigated with four different samples: (1) a mixture of C7−C30 saturated alkanes, (2) a multianalyte mixture consisting of 20 compounds ranging from 80 to 238 °C in boiling point, (3) a mixture of five organic chemicals with varying degrees of polarity, and (4) 46-compounds mixture containing all the chemicals in the first three samples. The individual columns separated 75%−100% of the first three samples but failed to distinguish all 46 compounds due to coeluting analytes; however, the parallel configuration provided more retention time information by which all the compounds in all samples were fully determined.



INTRODUCTION

Quantifying volatile and semivolatile organic chemicals (VOCs) is crucial in solving numerous problems including exposure assessment to toxic chemicals,[1] medical diagnosis,[2] pollution monitoring in air and water,[3] and indoor air quality measurements.[4] As the analysis of VOCs in complex samples usually requires separation prior to detection, gas chromatography (GC) has become one of the most useful pieces of laboratory equipment for a wide range of applications. Most GC instruments use a single column and a single chromatographic analysis. However, as the sample complexity increases or the column length is shortened for faster analysis, utilizing a single column may not provide the required separation power. One way in dealing with complex mixtures is to perform GC analysis by utilizing more than one column.[5,6] According to classical terminology, chromatography separation is called two or multidimensional when the separation of targeted components is repeated in two or more separation columns with different polarities, which are coupled in series or parallel to the column by which the first separation occurred.[7] According to the stringent theoretical definition, separation where the transfer of eluate cuts from the first column to other columns should be called multidimensional if significant improvement in separation is achieved.[8] The commonality between the two definitions is to use more than a single column with different stationary phase polarities for GC analysis. The objective of multicolumn GC can be increasing peak capacity, achieving high resolution for isomers and enantiomers, analyzing the sample in a shorter time, improving the determination of trace component, and separating coeluting compounds in the first column.[9,10]

As the length of the columns become shorter for either fast GC analysis or portable GCs, the use of multiple columns becomes more critical especially when the sample is more heterogeneous in terms of compound polarity. A single nonpolar stationary phase cannot adequately separate all compounds. This becomes an exciting avenue for research and development, in particular, for micro gas chromatography (μGC) systems enabled by the advancement in microelectromechanical systems (MEMS) technology. MEMS-enabled separation columns are typically short (<3m in length) and are intended for field-use applications. The earliest report on the MEMS GC was in 1979 around 20 years after the first GC instrument was introduced.[11] The 1.5 m-long column was etched into a silicon substrate with a wet etching technique. The analysis time was short, but separation of the closely related chemicals was not as good as the conventional GC system. Over the past couple of decades, significant progress has been made in column miniaturization using MEMS technology and in their stationary phase coating.[12] The

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advantages of the MEMS columns include batch fabrication and lower cost, fast analysis time with less power consumption, and decreasing the dead volume through monolithic integration with other components of μGCs.[13−15] Using columns fabricated by a deep reactive ion etching technique, our group has developed multicapillary columns, width-modulated columns, semipacked columns, and recently, density-modulated semipacked columns.[16−18] Our group, as well as others, have shown that successful separation of multianalyte gas mixtures can be achieved using 0.5−3 m long columns.[19,20] While the early reports showed columns with the number of theoretical plates close <2000 plates/m, over the past few years, more columns have been demonstrated that can achieve efficiencies beyond 5000 plates/m.[11,17,21] A comprehensive review of MEMS columns and future trends can be found in several review articles.[12,22,23] One example of significant research includes the report of the University of Illinois with 16 500 theoretical plates for 3 m-long microfabricated columns coated with OV-5 connected to 0.5 m long fused-silica tubes. The performance of this column was evaluated for the detection of 16 organic volatile compounds mixture.[24] However, the separation results included several coeluting peaks. Besides, diesel, polycyclic aromatic hydrocarbons (EPA 8310), enantiomer compounds, kerosene, and fatty acids have been partially or fully separated with MEMS columns depending on the sample complexity.[25−29] Another highly efficient MEMS chip-based multicapillary column was reported at Vrije Universiteit Brussel.[30] The theoretical plate numbers of 12 500 for hexadecane were achieved. Along with the development of micro columns, several multidimensional micro-GC were also developed. Liu et al. proposed a novel two-dimensional micro-GC system that includes a one-dimensional column, multiple parallel two-dimensional columns, and a decision module.[31] The separation of a mixture of 20 analytes and a mixture of plant emitted VOCs were shown using the adaptive GC system in 650 s, and 1270 s, respectively. Lambertus et al. also investigated dual microfabricated columns connected in series.[32] They reported 5000−6000 theoretical plate numbers for each column. Two columns together were able to separate 14-compounds mixture.

In addition to the geometrical features of a μGC column, the stationary phase has a significant impact on chromatographic performance. Polyethylene glycol (PEG), porous polymer beads and carbon molecular sieves (carboxen 1000) have been used in packed columns.[15,33,34] Derivatives of polydimethylsiloxane (PDMS) such as OV-1, OV-5, OV-101, OV-215 have been employed in open rectangular and semipacked MEMS columns.[25,35] In this paper, we focus on MEMS semipacked columns positioned in a parallel architecture and demonstrate how their selectivity can be tuned to achieve more complex sample analysis. With this configuration, a single analyte can generate multiple retention times enabling the identification of compounds that may coelute when using only a single column. To achieve the required selectivity, we employed ionic liquids (ILs) as the MEMS column stationary phase. There is an ongoing interest in using ILs as a stationary phase in conventional GC columns and more recently in MEMS columns.[29,36,37] A comprehensive review about IL properties and their behavior as gas chromatography stationary phase can be found in Poole and Zhao articles.[38,39] ILs have considerably high thermal stability with low melting points making them suitable for temperature-programmed separations. Another advantage of ILs in comparison to traditional stationary phases is their multiple solvation interaction capabilities that provide selectivity toward a variety of compounds.[40] Our group has previously reported the use of ILs namely [BPY][NTf_2] and [P_{666}][NTf_2] in semipacked MEMS columns. We have already shown that changing IL can tune selectivity. Furthermore, higher separation efficiency could be achieved if the interior surfaces of the columns are coated with a thin layer of alumina deposited using atomic layer deposition (ALD).[21] Here, we use three different ILs, for the first time, to coat semipacked columns configured in parallel to analyze more complex chemical matrices. The selection of an appropriate stationary phase based on polarity and the functional group led to high separation powers with reproducible results and demonstrated superior compound identification when using retention times generated by more than one column. The following details the column design, coating, separation of different test mixtures, and compound identification power using combinatorial retention times extracted from the MEMS columns.

MATERIALS AND METHODS

Chemicals and Materials. Three RTILs, namely, 1-butylpyridinum bis(trifluoromethylsulfonyl)imide ([BPY][NTf_2] (IL1), 1-(2-hydroxyethyl)-3-methylimidazolium bis(trifluoromethylsulfonyl)imide [HOEMIM][NTf_2] (IL2), and methyltrioctylammonium bis(trifluoromethylsulfonyl)imide [N1888][NTf_2] (IL3) were obtained from Ionic Liquids Technologies, Inc. (Tuscaloosa, AL). NTf_2 was chosen as the anion part because of its good thermal stability.[41] Silicon wafers (n-typed, 4 in. diameter, 500 μm thickness, and double sided polished) and Borofloat wafer (4 in. diameter, 175 μm thickness) were purchased from University Wafer, Inc. (Boston, MA). Fused silica capillary tubes with 100 μm internal diameter and 200 μm outer diameter were purchased from Polymicro Technologies, LLC. (Lisle, IL, US). JB Weld epoxy was obtained from local store. Acetone, naphthalene, heptane, octane, nonane, benzene, toluene, ethylbenzene, p-xylene, m-xylene, o-xylene, isobutylbenzene, styrene, butylbenzene, 1,2-dichlorobenzene, 2,5-dichlorotoluene, 1,2,4-trichlorobenzene, benzyl chloride, 2-nitrotoluene, 3-nitrotoluene, 4-nitrotoluene, butanol, nitropropane, pyridine, pentanone, and standard of C7−C30 saturated alkanes (1000 μg/mL for each compound in hexane) were purchased from Sigma-Aldrich (St Louis, MO). Ultrapure helium, nitrogen, air, and hydrogen were obtained from Airgas, Inc. (Christiansburg, VA). Part catalog number of the chemicals was provided in the Supporting Information. Different mixtures were created using the above chemicals. Sample 1 includes C7−C30 saturated alkanes. Sample 2 contains naphthalene, heptane, octane, nonane, benzene, toluene, ethylbenzene, p-xylene, m-xylene, o-xylene, isobutylbenzene, styrene, butylbenzene, 1,2-dichlorobenzene, 2,5-dichlorotoluene, 1,2,4-trichlorobenzene, benzyl chloride, 2-nitrotoluene, 3-nitrotoluene, and 4-nitrotoluene with a concentration of 0.5% w/v for each compound to the total sample volume. Sample 3 includes benzene, butanol, nitropropane, pyridine, and propane with a concentration of 0.5% w/v for each compound in heptane. All solutions were kept in the refrigerator before using.

Instrumentation. All gas chromatography measurements to characterize the performance of MEMS columns coated with ILs were performed in an Agilent 7890A GC (Agilent Technologies, Inc., Santa Clara, CA) system equipped with an automatic sampler (7693A), a split/splitless inlet, and a flame

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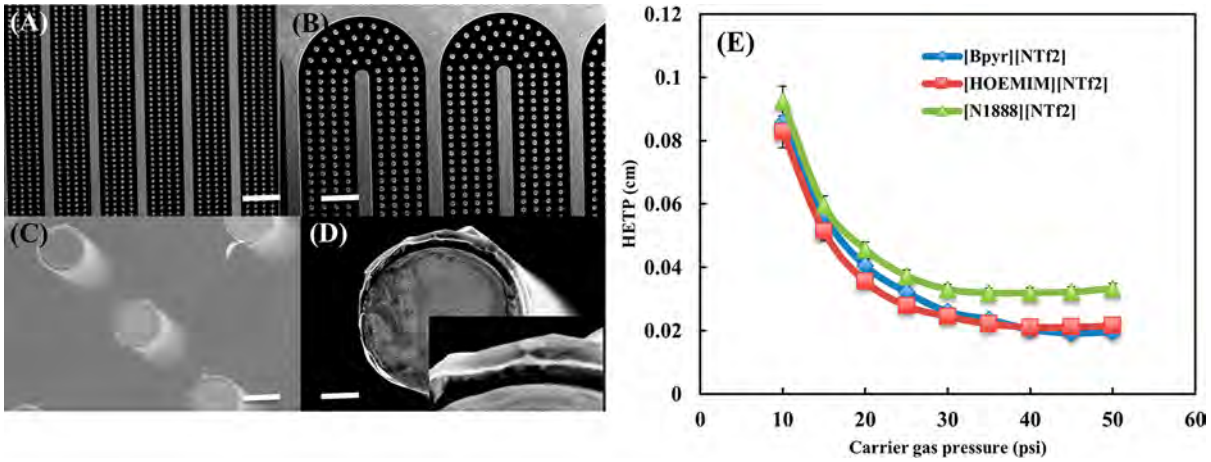

Figure 1. (A) SEM image of the semipacked column from the top, (B) a closer SEM image showing the pillars from the top, (C) cross view of the coated pillars with 15 mg/mL [BPY][NTf_2] ionic liquid, (D) Magnified image of the uniform coated layer of ionic liquid around the silicon micropillar, and (E) Golay plot for [BPY], [HOEMIM], and [N1888][NTf_2] ionic liquids. Injection volume 0.1 μL, split ration 200:1, inlet, detector and oven temperature 280, 300, 100 °C, respectively. Scale bars in SEM images are, respectively, 200 μm, 150 μm, 16 μm, and 3 μm.

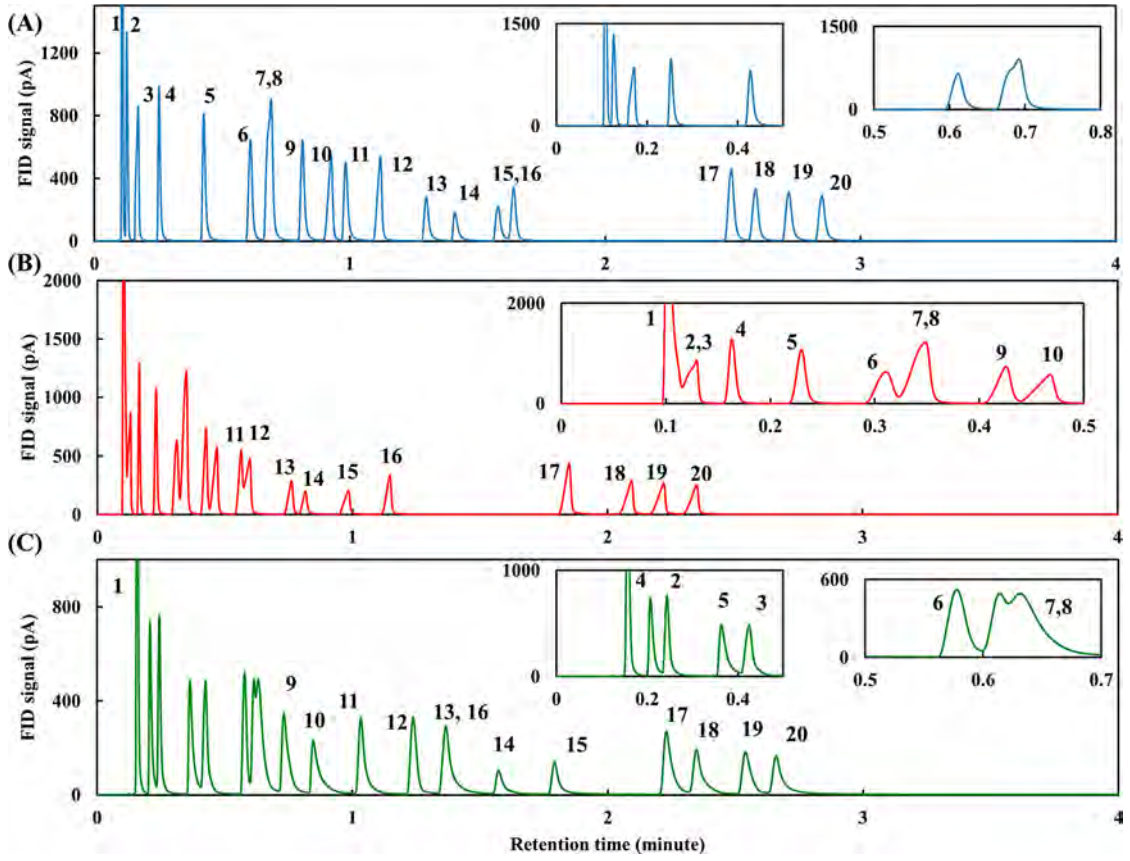

Figure 2. Chromatograms showing the separation of a 20 component mixture of organic compounds using (A) [BPY][NTf_2], (B) [HOEMIM][NTf_2], (C) [N1888][NTf_2] based stationary phases. Condition: injection volume 0.3 μL, split ratio 200:1, carrier gas pressure 20 psi, initial oven temperature 30 °C; ramp rate 40 °C/min to 200 °C and held for 2 min. The retention time of the chemicals is listed in Table S1.

ionization detector (FID). Helium was used as a mobile phase. The temperatures of the inlet and the detector were held at 280 and 300 °C, respectively. The hydrogen and air gases were used in the FID detector. The flow rate of hydrogen and air were kept at 30 mL/min and 300 mL/min, respectively, for all the measurements. SEM images were obtained using Carl (Zeiss) EVO 40 scanning electron microscope (SEM). The data were analyzed using the Agilent ChemStation Edition C.01.04 and the Matlab software. The elution of each compound was determined individually for all stationary phases.

Preparation of the IL-Based GC Columns. The detail of the fabrication of the semipacked columns was discussed in our previous report.[21] Concisely, the fabrication of the semipacked GC columns includes six steps. The fabrication detail was included in the Supporting Information.

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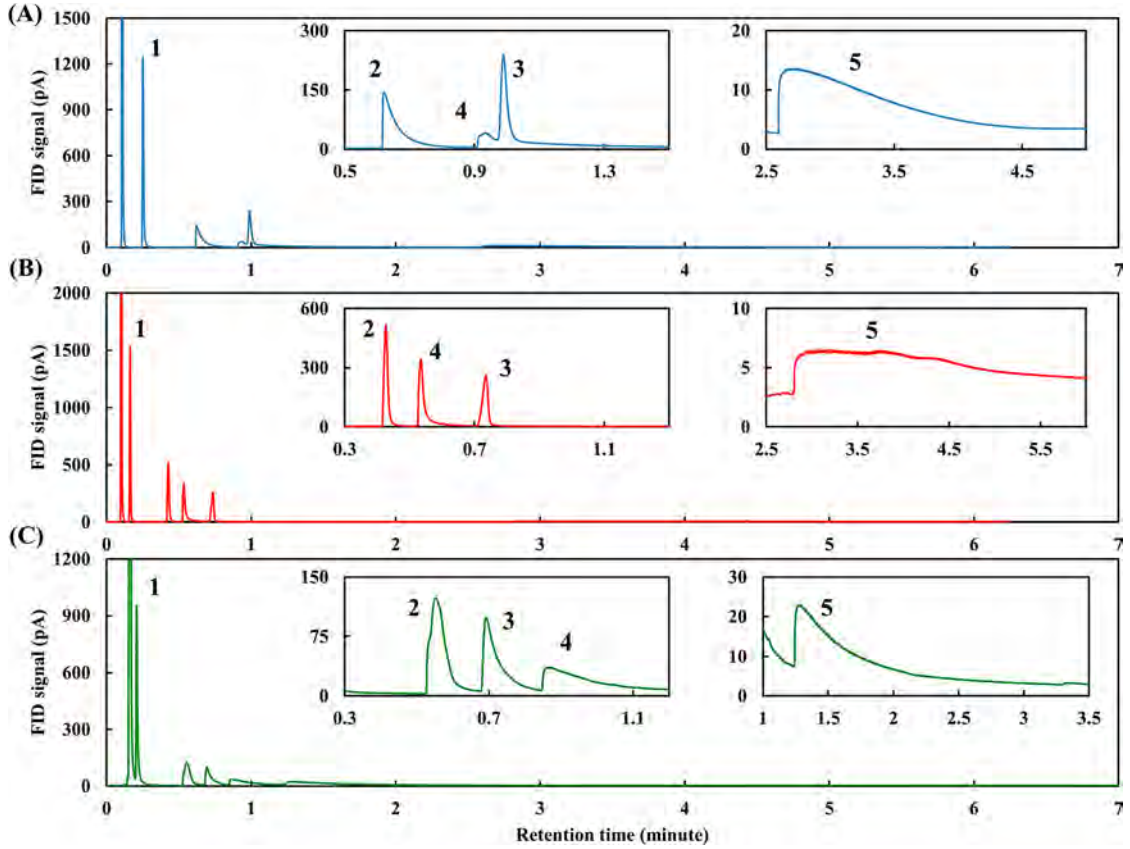

Figure 3. Chromatograms showing the separation of a five component mixture of polar standard chemicals using (A) [BPY][NTf_2], (B) [HOEMIM][NTf_2], (C) [N1888][NTf_2] based stationary phases. Condition: injection volume 0.3 μL, split ratio 200:1, carrier gas pressure 20 psi, initial oven temperature 30 °C; ramp rate 40 °C/min to 200 °C and held for 2 min. (1) Benzene, (2) pentanone, (3) nitropropane, (4) butanol, (5) pyridine. The retention time of the chemicals is listed in Table S1.

To coat the columns with stationary phases, first, the outlet and inlet of the fabricated columns were attached to 30 cm-long fused silica capillary tubing using JB Weld epoxy and allowed to cure for 2 h at 80 °C. Following attachment of the capillary tubes to the columns, they were coated with the stationary phases. The modified static coating technique was used to cover the columns with the stationary phases. First, the IL filled the column completely, and then nitrogen gas was used to purge the solvent and to dry the columns. We used nitrogen purging rather than using vacuum as it avoided the formation of bubbles in the channels. IL1 and IL2 were prepared with a concentration of 15 mg/mL in acetone. For IL3, we used 1.5 mg/mL in acetone as it was much more viscous compared to the other two. Freshly prepared solutions were injected inside the columns using a 1 mL syringe pump with the initial flow rate of 20 μL/min that fills the 1 m column in around 4 min, the process was followed by two steps of solution injection with flow rates of 40 and 60 μL/min to cover the possible uncoated residue spots. After forming a uniform coating without bubbles, the extra ionic liquid and solvent were removed by using nitrogen gas at a pressure of 10 psi while the column was kept in a water bath at a constant temperature of 40 °C. After this step, the ionic liquid phases were annealed overnight at 240 °C inside an oven.

RESULTS AND DISCUSSION

Characterization of the Stationary Phases. SEM imaging was used to investigate the uniformity of the stationary phases on silicon pillars as shown in Figure 1. This is the first time that the coating of microcolumn with a IL stationary phase is viewed from the topside and hence is very significant. Figure 1A,B demonstrate the top view of the four pillar arrays inside the column. Figure 1C,D show the coated layer of the IL1 around the pillars. IL was uniformly coated around the pillars, and based on the SEM image of the top sheets; the thickness of ionic liquid layer is around 220 nm. The calculation provided in the Supporting Information shows that the thickness for IL1 and IL2 are close to 200 nm, whereas that for the IL3 column is around 26 nm. The calculated thickness for IL1 is in good agreement with the obtained number from the SEM image. The column efficiency was evaluated by measuring the number of theoretical plates (N) using 5% (w/v) naphthalene in heptane solution at 100 °C.[42] Then, the height of equivalent-to-a-theoretical plates (HETP) was plotted under different carrier gas pressure conditions (Figure 1E). The optimum pressure of the carrier gas was found to be 45 psi with the maximum number of the theoretical plates of 8316/m for IL1, 7559/m for IL2 at 45 psi (k for naphthalene is 11.5 and 4, respectively, at an inlet pressure of 45 psi), and 5019/m for IL3 at 35 psi (k for naphthalene is 7.8 at an inlet pressure of 35 psi). These observations indicate that highly efficient separation columns with all three ILs can be achieved. One possibility for the differences observed in the Golay plots between IL3 and the other two columns can be due to the changes in the stationary phase viscosity and the thickness.

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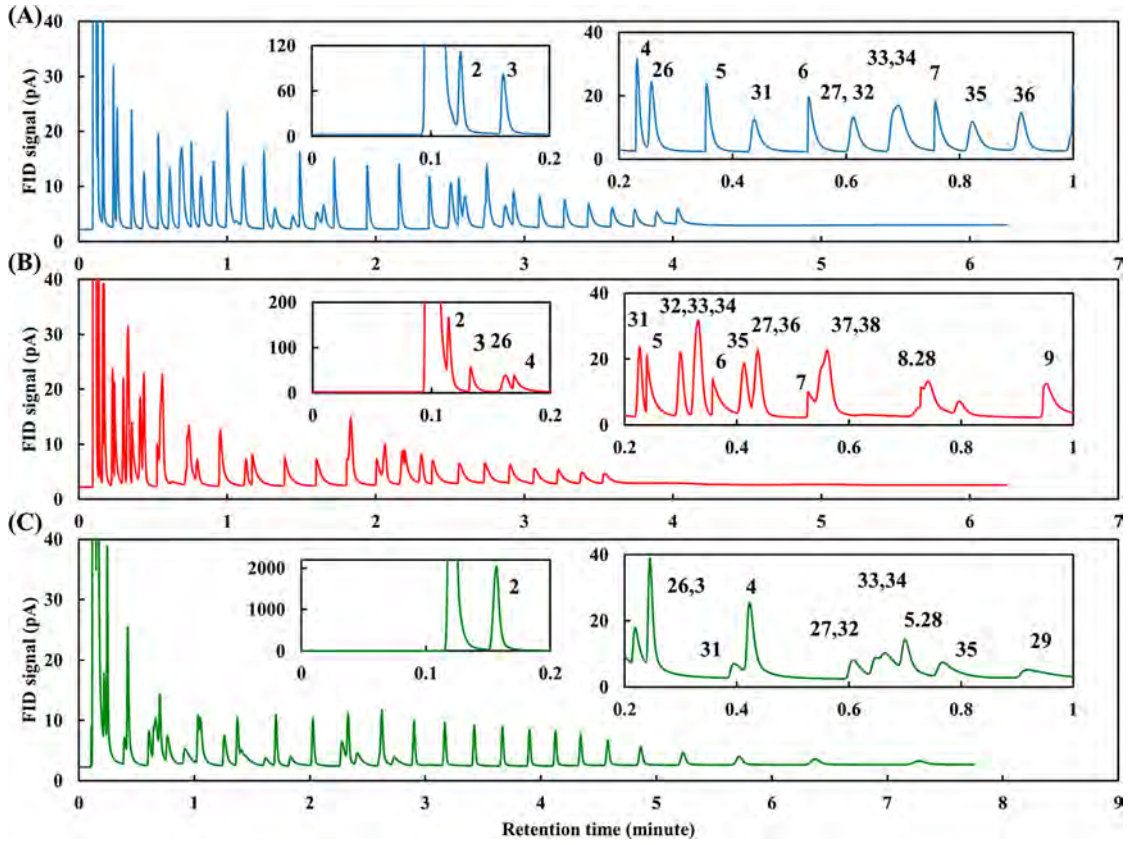

Figure 4. Chromatograms showing the separation of a 46 components mixture of organic compounds using (A) [BPY][NTf_2], (B) [HOEMIM][NTf_2], (C) [N1888][NTf_2] based stationary phases. Condition: injection volume 0.3 μL, split ratio 200:1, carrier gas pressure 20 psi, initial oven temperature 30 °C; ramp rate 40 °C/min to 200 °C and held for 2 min. The retention time of the chemicals is listed in Table S1.

Chromatographic Analysis. The separation of C7−C30 alkanes was performed as the standard nonpolar analytes (Figure S1). The columns of IL1, 2, 3 were able to separate the saturated alkanes in 3, 2.9, and 7.6 min, respectively. More details regarding the separation are provided in the Supporting Information.

Sample 2 is a 20-compound mixture consisting of saturated alkanes, aromatic halides, aromatic hydrocarbons, and nitro aromatics. The boiling points of the compounds are in the range of 80 °C for heptane and 238 °C for 4-nitrotoluene. The list of these compounds and their retention time for different ILs and temperature programing situations are presented in Tables S1 and S2. These hazardous chemicals are widely present in various environmental samples. Figure 2A−C shows chromatograms for the separation of the mixture using ILs with a ramp of 40 °C/min. The chromatogram for 20 components was also obtained with a temperature ramp of 100 °C/min (Figure S2). The faster temperature ramp was applied to show that separation also occurs in a shorter time but still provides very good separation resolution. The resolution value between the peak of interest and the preceding peak was represented. (Table S3). The IL1 gives better resolution between naphthalene and benzyl chloride with a value of 22.6, whereas IL3 gives the lowest with a measured amount of 8.8. Among them, only IL3 is able to separate p- and m-xylene. For IL3, there is an overlap between peaks of benzyl chloride and 1,2 dichlorobenzene. For IL2, there is some overlap between nonane and benzene. Another interesting observation is that the elution order for IL1 and IL2 are similar but it is not the case for IL3 column. This is reaffirmation that the ionic liquid nature plays a high role in the selectivity toward analytes.

The Chemical Interactions of the Stationary Phases. Figure 3 shows the response of the ionic liquids regarding chemical interaction probe molecules using a temperature ramp of 40 °C/min. We also performed chromatographic analysis at a ramp of 100 °C/min, and the components were separated in less than 3 min for all stationary phases. Pyridine, however, shows large bond broadening. This explains that the chemical interaction is a predominant factor for band broadening as opposed to the temperature programing in this case. All phases responded to benzene very well. IL2 column has a lower retention time compared to others. Besides, it has better interaction with butanol because of the presence of OH groups. That makes IL2 suitable for alcoholic based compounds mixtures. Based on their response toward pyridine, three ILs used in this research do not show a good hydrogen bond interaction. Because of the active electron donor group of OH in IL2, pyridine peak shows higher retention time and more tailing; on the contrary, IL3 has a more symmetric peak and a shorter retention time, as is the less polar stationary phase (Figure S3). In addition to chemical interaction, another reason for bond broadening is the effect of temperature programming. Looking at the resolution equation, the temperature will mainly impact the $k/k+1$ term. When k is low, reducing the temperature will increase this term in a nearly linear way, which directly impacts the resolution. Additional details of stationary phases classification are provided in Figure S4, Tables S4 and S5.

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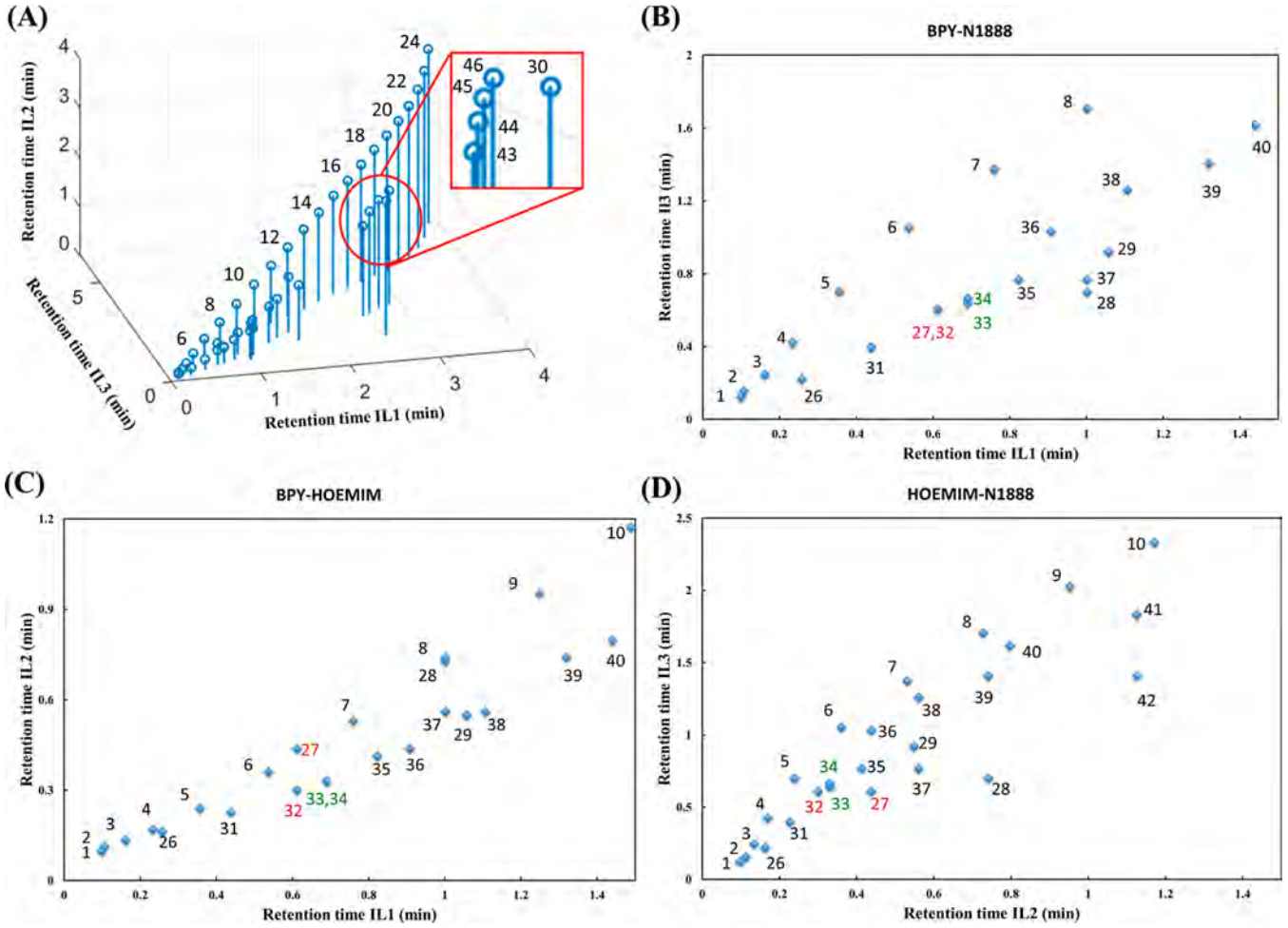

Figure 5. (A) 3D plot of retention time of 46 compounds for [BPY][NTf_2] (IL1), [HOEMIM][NTf_2] (IL2), [N1888][NTf_2] (IL3), (B) 2D plot of retention time in the range of 1.5 min for IL1, IL2, (C) 2D plot of retention time in the range of 1.5 min for IL1, IL3, (D) 2D plot of retention time in the range of 1.5 min for IL3, IL2. Condition: injection volume 0.3 μL, split ratio 200:1, carrier gas pressure 20 psi, initial oven temperature 30 °C; ramp rate 40 °C/min to 200 °C and held for 2 min. The retention time of the chemicals is listed in Table S1.

Pseudo-2D Parallel Gas Chromatography Approach. To evaluate the ability of the proposed method as a pseudo-2D gas chromatography, the mixture containing 46-chemical compounds was analyzed using all three columns. The list of these compounds is mentioned in Table S1. The separation was conducted at 20 psi helium pressure. Two temperature programming ramp rates were used: 40 °C/min and 100 °C/min from 30 to 200 °C. The temperature was kept at 200 °C for 2 min. Figure 4 depicts the response of the three stationary phases for 40 °C/min. Figure S5 shows the chromatograms with the ramp of 100 °C/min. From the retention time data, the responses of three columns are distinctly different, especially in the first minute of the separation. This gives the ability to analyze more compounds in a shorter period of time. None of the columns were able to separate all 46 compounds as can be seen by the color-coded coeluting compounds. The data also show the presence of more coeluting compounds with a higher temperature ramp. It should be noted that coeluting compounds are not the same for three ionic liquid phases. For example, for IL1 case, groups of 27/32, 8/28/37, and 30/44 have overlapping peaks; for IL2, groups of 18/30, 27/36, 28/39, 37/38, and 41/42 have the same retention time. This suggests enhanced identification of these components is possible by the parallel operation of these three ionic liquids at once (Tables S1, S2, and Figure S6).

Figure 5, shows multidimensional plots of the retention times of all 46 chemicals for the three different ionic liquids. For each compound, there are three different indicators in contrast to using only a single column. Since most of the coeluting compounds have retention times below 2 min, Figure 5B–D shows the 2D plots of retention times for the temperature ramp of 40 °C/min for the first 2 min. It is evident that three compounds of C13 (8), nitropropane (28), and styrene (37) have all the same retention time of about 1 min for IL1. These compounds have entirely different retention times in IL3 stationary phase as 1.7, 0.7, and 0.92 min, respectively. In addition, pentanone (27) and ethylbenzene (32) coelute in both IL1 and IL3 but they are only separable using IL2. Using IL1 and IL3, 44 compounds can be determined. This clearly indicates that by applying three stationary phases at the same time, we can identify all 46 compounds. As the potential of the proposed micro columns configuration was verified for 46 compounds, we can expand the chemical lists and create a lookup table that contains the retention time for all three columns. Furthermore, we can envision using these columns in conjunction with a MS system to generate the lookup table.

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It is essential to note that we have done the same analysis for chromatograms obtained at a ramp rate of 100 °C/min. Table S2 summarizes the retention times of all compounds with coeluting compounds identified by different colors. The increased ramp rate decreases the total analysis time by about 30% but at the cost of more coeluting compounds in every single column. However, the methodology presented for the slower ramp was applied to this case too, and all the compounds in the complex mixture were correctly identified using all three retention times. This, again, is verification that for fast analysis using short MEMS columns, the use of stationary phase selectivity in a parallel configuration will drastically enhance the system performance.

CONCLUSION

The data presented in this paper are proposing the parallel configuration of the micro GC columns with applying ionic liquids of different polarity as the stationary phases. The use of multiple columns increases the available information for each compound while preserving the total analysis time. The data from the three stationary phases in this work gave 100% compound identification power while each column separately could identify at most 85% of the chemicals in the 46-compound mixture. Although this is less powerful compared to a 2D GC (GC×GC), its implementation is much more convenient, resulting in reduced cost, increased portability, and reduced extra fluidic and electronic components. The work presented here can be expanded to include more complex mixtures addressing a wide range of applications especially when interfering compounds in the environment becomes detrimental and makes it challenging for target compound identification using a single column. Our future work is to implement the parallel GC configuration presented here on a single chip and to integrate each column with its own detector using our previously published work.[35,43,44] Furthermore, we enhance the complexity of the chemicals as well as exploring new ionic liquids with a wide range of polarities to identify the constituents of mixtures with more than 100 compounds in just a few minutes.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.analchem.0c01721.

Chromatogram of saturated alkanes; 20 organic, polar, and mixtures of 46 compounds with ramp rate of 100 °C/min; list of chemical retention times; resolution and retention index data (PDF)

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Notes

The authors declare no competing financial interest.

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