

Comparison of Frequency-counter- and Vector-network-analyzer-based Measurement Systems for Quartz Crystal Microbalance Gas Sensor Array

Sudipta Kumar Sarkar,^{1,2} Ziteng Bao,³
Manuel Aleixandre,¹ and Takamichi Nakamoto^{1,3*}

¹Institute of Integrated Research, Institute of Science Tokyo, Yokohama 226-8501, Japan

²School of Electronics Engineering, Vellore Institute of Technology, Vellore, Tamil Nadu 632-014, India

³School of Engineering, Institute of Science Tokyo, Yokohama 226-8501, Japan

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Quartz-crystal microbalance (QCM)-based gas sensors are well known for their lightweight structure, simple operation, high sensitivity, and limit of detection (*LOD*). The use of a QCM sensor array further enhances selectivity and enables the quantification of gas mixtures. However, the performance of QCM sensors in practical system is strongly influenced by the characteristics of measurement system, used for capturing their output frequency signals. A vector network analyzer (VNA) and a frequency counter (FC) are two common examples of such measurement systems, each offering distinct advantages and limitations. In this study, the performance of these two measurement systems is systematically investigated and compared for trace-level gas detection using QCM sensors. Herein, four different volatile organic compounds (VOCs) including isobutyric acid (IBA), trans-2-hexenal (T2H), 1-butanol (1-B), and butyl isobutyrate (BIB) were selected as analyte gases, whereas for comparison, four-channel measurement systems based on both VNA and FC were developed. These four-channel measurement systems were used to capture real-time signals from an array of four QCM gas sensors, which were coated with polyethylene glycol 1000 (PEG), 1,2,3-tris (2-cyanoethoxyl propane) (TCEP), thermol-1 (THML), and polyphenyl ether (five rings) (PPE). The concentration of each analyte gas was varied to determine sensitivity and *LOD* for both measurement systems. A significant difference in *LOD* was observed for IBA with a PPE sensor. *LOD* was found to be 4 ppm (estimated from the relative concentration) for VNA and 30 ppm for FC. Although both measurement systems performed excellently in detecting very low concentrations of analyte gas, VNA offered a much lower *LOD* than FC owing to the fundamentally higher instrument resolution of VNA than of FC. Hence, we make an overall comparison between the FC- and VNA-based measurement systems for QCM gas sensing application, and the results can be considered as a key reference point for further research in this field.

*Corresponding author: e-mail: nakamoto.t.73a7@m.isct.ac.jp
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1. Introduction

Over the years, the quartz crystal microbalance (QCM) has been highly recognized for sensing applications. This is primarily due to its light weight structure and mass-based sensing mechanism enabling simple and portable operation, easy handling, reliable performance and high sensitivity.^(1,2) The resonance frequency that serves as the sensor signal in a QCM oscillator changes significantly even in response to the minute mass variation caused by the binding of external molecules on the QCM surface.⁽³⁾ Owing to this high sensitivity to mass changes, QCMs have been extensively studied for use in gas sensing applications.⁽⁴⁾ Generally, the QCM surface is coated or functionalized with a specific binder to selectively detect gas molecules.^(5,6) A variety of sensors are available. We used a QCM sensor since various sensors can be realized just by changing the sensing film.⁽⁷⁾ Hence, an array of QCM sensors with different coatings exhibits different response patterns from sample to sample that can be used to quantify a gas mixture. In our previous study, we reported gas mixture quantification with an array of QCM gas sensors.^(8,9)

However, the effective performance of a QCM-based gas sensor in practical systems largely depends on the measurement system employed to capture its frequency signal.^(10–12) Parameters such as the limit of detection (*LOD*), response, and recovery time are largely affected by the integrated measurement system. Although frequency counters (FCs) are often used in QCM measurement, vector network analyzers (VNAs) are also available.^(10,13–14) Although VNAs were originally bulky and expensive, we can nowadays use inexpensive small VNAs. Moreover, VNA can collect information on resonance–resistance change as well as harmonics information even in real time, which enhances the sensing information from QCM. Normally, the *LOD* of VNA is low if appropriate signal processing is implemented.⁽¹⁵⁾ However, little is known about *LOD* improvement compared with a simple FC measurement. Thus, we measured QCM responses by both the FC and VNA methods under the same conditions and investigated the impact of different measurement systems on the performance of QCM-based gas sensors.

To date, QCM gas sensors with FCs have been used in most studies. In our previous studies, we developed and reported both the multichannel FC- and multichannel VNA-based measurement systems for acquiring signals from an array of QCM gas sensors.^(16,17) However, those studies were mainly focused on the sensor's application in gas mixture quantification, not on the performance of the measurement system used.⁽¹⁸⁾

Therefore, in the present work, emphasis is placed on the measurement systems used for a QCM-based gas sensor array. In this study, our previously designed and developed four-channel FC and four-channel VNA were used separately with an array of the same four QCM-based gas sensors. The objective is to compare the performance characteristics of these two measurement systems. The four different volatile organic compounds (VOCs) reported in the previous study⁽⁹⁾ were selected as analyte gases. Various concentrations of these analytes were introduced into the QCM sensor array, and the resulting frequency shift was measured using both FC and VNA. Each QCM sensor in the array was functionalized with a different coating layer to facilitate the selective binding of the analyte gases; consequently, each sensor produced a unique response. The real-time signal from each sensor was acquired by FC and VNA in a four-channel configuration. Thus, for each analyte gas, signals from four different sensors were recorded

using both FC and VNA, and the captured signals were subsequently used to compare the performance characteristics of these two measurement systems.

Although VNA provides much information, the signal-to-noise ratio is not always good when we use only the standard method to track the frequency with a conductance peak. Since the whole information of the QCM frequency characteristic is used in our method, the noise can be markedly reduced as was reported in the previous work,⁽¹⁵⁾ where QCM in the liquid phase was used. In the current work, we applied that method to the gas sensing and confirm its effect by comparing it with FC under the same measurement conditions.

2. Experiment

2.1 Materials

The four VOCs used as test gases are isobutyric acid (IBA), trans-2-hexenal (T2H), 1-butanol (1-B), and butyl isobutyrate (BIB) from TCI chemicals. They are ingredients of the apple flavor.⁽⁹⁾

2.2 Sensor array fabrication

The sensor array reported in this study consists of four QCM sensors (SEIKO EG & G AT-cut), each fundamental resonance frequency of which was approximately 9 MHz. Each QCM sensor was fabricated by coating its surface with one of the following sensing layers: polyethylene glycol 1000 (PEG), 1,2,3-tris (2-cyanoethoxy) propane (TCEP), thermol-1 (THML), and polyphenyl ether (five rings) (PPE). These sensing materials are commonly used as stationary phase materials in gas chromatography (GC). Dip coating was used to deposit the sensing film on the QCM surface.⁽⁸⁾ The four QCM sensors were set in a sensor cell with the proper gas flow arrangement. O-ring sealants were used in the sensor cell to avoid leakage.⁽¹⁷⁾

2.3 Gas flow setup

The test gases were introduced to the sensor array using an odor blender system. One test gas was introduced at a time. The odor blender system consists of an air–gas mixing and delivery unit (Fig. 1) in which a solenoid valve regulates the concentration of each gas by adjusting the gas mixture ratio.⁽¹⁹⁾ The flow rate at the QCM sensor array was 202 mL/min.

2.4 Measurement system

Both the FC- and VNA-based measurement systems used in this study were developed in-house. The FC-based measurement system comprised an oscillator circuit (NJU6322L, New Japan Radio Inc.) and an FC, such as a binary modulus counter, built on a field-programmable gate array (FPGA, Altera Cyclone 5 SE 5CSEMA5F31C6N) board. Four-channel FC-based measurement systems were subsequently realized by integrating four identical FC-based measurement systems in parallel on the same FPGA. The outputs of this multichannel measurement system were recorded on a computer using an in-house-built MATLAB platform.

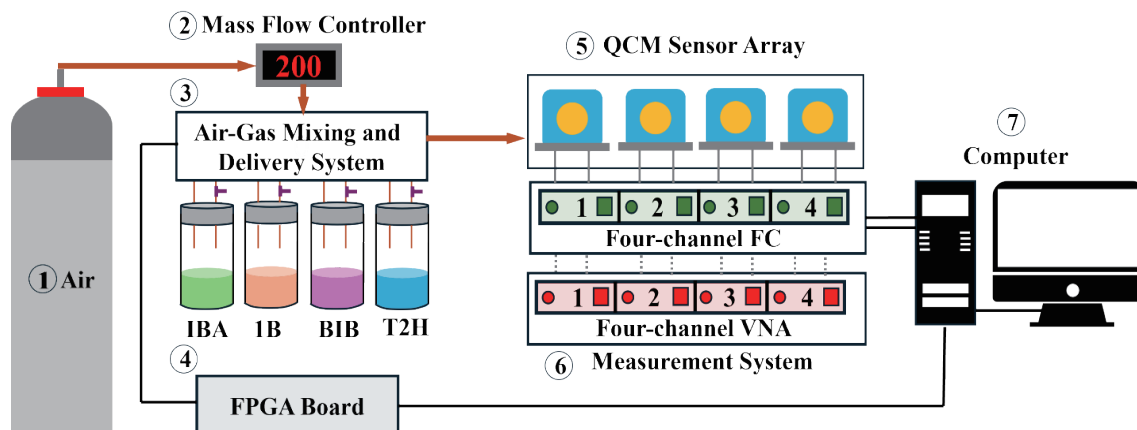


Fig. 1. (Color online) Schematic illustration of experimental setup.

The four-channel VNA system was realized using four commercial VNAs (DG8SAQVNWAv3) connected in parallel with the sensor array. Each VNA measures the frequency characteristic of QCM conductance and was fitted into a QCM equivalent circuit model to determine the value of each component in the equivalent circuit. Moreover, a Savitzky–Golay filter was used to improve S/N ratio without signal distortion. A MATLAB code was used to record the resonance frequency values in real time. FC and VNA have been compared in blood viscosity measurement but not in a gas measurement system.⁽²⁰⁾

3. Results and Discussion

The performance characteristics of both the four-channel FC- and VNA-based measurement systems were evaluated using the real-time signals acquired from the sensor array. Figure 2 illustrates the responses of four sensors to IBA, while Figs. S1, S2, and S3 show the corresponding real-time responses to T2H, 1-B, and BIB, respectively. The concentration [%] of each analyte gas reported in this work is relative to full-scale concentration.⁽¹⁹⁾ The concentration was varied by simply controlling the volume of gas entering the sensor cells by switching the solenoid valves. To compare the performance between VNA and FC, the *LOD* values were estimated for both systems where *LOD* was defined as the minimum concentration of analyte gas for which a statistically significant response was achieved. Statistical t-tests were performed to determine the significance, and five independent measurements were taken for performing the t-test. The confidence level was 0.05. The values are listed in Table 1. To compare the sensitivity of the sensors to each analyte gas, sensor responses are plotted against the concentration in Figs. 2(d), S1(d), S2(d), and S3(d).

Figures 2(a)–2(c) show the real-time responses of all four sensors (PEG, TCEP, thermol, and PPE) to IBA across various concentrations. It can be clearly observed in Figs. 2(b) and 2(c) that the minimum frequency shift detected by the FC-based measurement system is 1 Hz, whereas it is much lower with the VNA-based measurement system, indicating that the instrument resolution offered by the VNA-based measurement system is higher than that offered by the FC-based measurement system. As can be seen in Figs. 2(a) and 2(b), at higher concentrations (> 10%), both the FC- and VNA-based measurement systems exhibit almost comparable responses

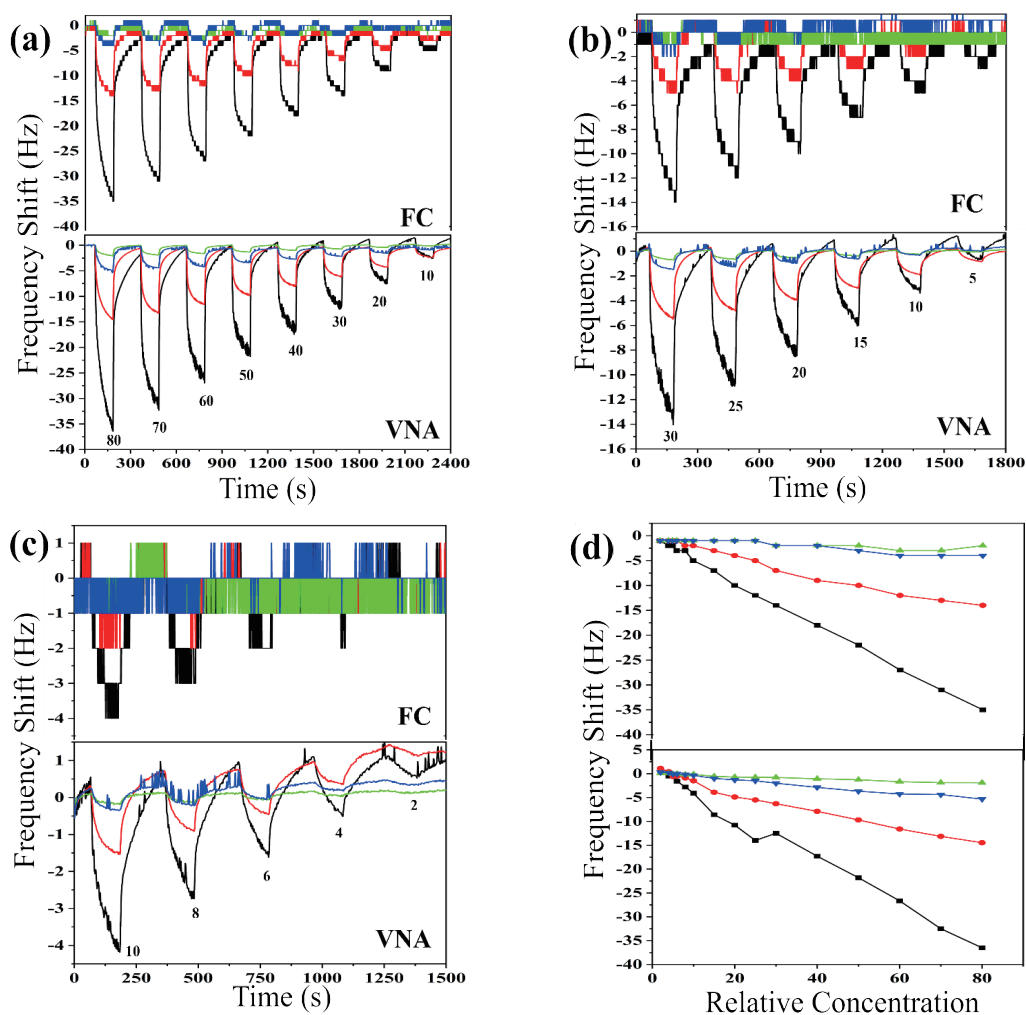


Fig. 2. (Color online) Real-time responses of all four sensors (data for PEG, TCEP, Thermol, and PPE sensors are shown in black, red, green and blue, respectively) in the (a) high, (b) medium, and (c) low concentration ranges of IBA as analyte gas when detected with FC- and VNA-based measurement systems. (d) Sensor response versus IBA concentration for both FC- and VNA-based measurement systems. The value at each peak indicates concentration [%] relative to the full scale 100.7 ppm.

for all four sensors. However, at lower concentrations (<10%), the FC-based measurement system slowly starts losing signals from the sensors and could only detect the signal from the PEG-coated sensor. On the other hand, the VNA-based measurement system was well able to capture signals from all the sensors for concentrations > 2% [Fig. 2(c)]. Hence, the *LOD* of the PEG-coated sensor was found to be 6 and 2% with the FC- and VNA-based measurement systems, respectively. The *LOD* values of all four sensors for IBA in the FC- and VNA-based measurement systems are listed in Table 1. It can be observed that for all four sensors, the *LOD* values were found to be much lower for the VNA-based measurement system than for the FC-based measurement system. This can be attributed to the fundamental difference in instrument resolution between these two measurement systems. However, from the plot of sensor response versus concentration in Fig. 2(d), similar trends are observed for both the FC- and VNA-based measurement systems. In both cases, the PEG-coated sensor was found to be the most prominent with the highest sensitivity. The similar sensitivity values of approximately 0.4 Hz per unit of

Table 1
Estimated LOD values for each analyte gas and sensor.

Analyte gas	Sensor	LOD (%)	
		FC	VNA
IBA	PEG	4	2
	TCEP	8	2
	Thermol	30	4
	PPE	30	4
T2H	PEG	15	6
	TCEP	50	4
	Thermol	50	10
	PPE	25	4
1-B	PEG	10	2
	TCEP	20	2
	Thermol	70	6
	PPE	50	4
BIB	PEG	70	6
	TCEP	5	4
	Thermol	25	4
	PPE	10	4

analyte concentration estimated with both the FC- and VNA-based measurement systems may indicate that the sensitivity of the QCM gas sensor is a fundamental property and therefore is not affected by the measurement system used.

Figures S1, S2, and S3 in the supplemental materials show the real-time responses of the QCM sensor array to the analyte gases T2H, 1-B, and BIB, respectively. The sensors with the highest sensitivity can be identified for these gases from the response versus concentration plots in Figs. S1(d), S2(d), and S3(d). The *LOD* values for each test gas were identified directly from the real-time curves and are listed in Table 1. It is important to note that irrespective of analyte gases and sensors, the *LOD* values observed with the VNA-based measurement system were lower than those observed with the FC-based measurement system. Simple methods of measuring the frequency with maximum conductance have large noise even when VNA is used.⁽¹⁵⁾ Thus, the curve fitting to the QCM equivalent circuit together with the use of the Savitzky–Golary filter contributes to the small noise when using the VNA-based measurement system. However, almost identical trends are observed in sensor responses [Figs. 2(d), S1(d), S2(d), and S3(d)] in the high-analyte-concentration range for both the FC- and VNA-based measurement systems, indicating that some of the fundamental characteristics of the QCM sensors do not depend on the measurement system used.

4. Conclusions

In the current study, we analyzed the performance of multichannel FC- and VNA-based measurement systems for QCM gas sensors. Four different VOCs were used as analyte gases, and for each analyte gas, a significant difference was observed among the *LOD* values obtained using the FC- and VNA-based measurement systems, indicating the fundamental resolution difference between these measurement instruments often used for acquiring QCM sensor signals. For the best performing sensors, the *LOD* values were obtained at relative concentrations

of 4, 15, 10, and 5% for IBA, T2H, 1B, and BIB, respectively, with FC-based measurement, whereas the *LOD* values with VNA measurement were found at relative concentrations of 2, 6, 2, and 4%, respectively, for same IBA, T2H, 1B, and BIB. Therefore, a clear difference was observed between the respective *LOD* values obtained with the FC- and VNA-based measurement systems.

Although the use of a small VNA becomes cheaper, it is still more expensive than FC measurement. However, it provides both frequency shifts and resistance changes of fundamental and harmonics. That information contributes to the accuracy improvement of the mixture quantification. In the future, it is necessary to evaluate the long-term stability we have not checked yet.

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References

1. F. N. Murrieta-Rico, V. Petranovskii, D. H. Galván, J. Antúnez-García, O. Sergiyenko, L. Lindner, M. Rivas-López, M. Grishin, and S. Sarvadai: *IEEE Sensors J.* **22** (2022) 10163. <https://doi.org/10.1109/JSEN.2022.3148039>
2. L. Wang, J. Song, and C. Yu: *Measurement* **249** (2025) 117039. <https://doi.org/10.1016/j.measurement.2025.117039>
3. S. N. Songkhla and T. Nakamoto: *Chemosensors* **9** (2021) 350. <https://doi.org/10.3390/chemosensors9120350>
4. W. H. King: *Anal. Chem.* **36** (1964) 1735. <https://doi.org/10.1021/ac60215a012>
5. Y. Cao, M. Fu, S. Fan, C. Gao, Z. Ma, and D. Hou: *ACS Appl. Mater. Interfaces* **16** (2024) 7721. <https://doi.org/10.1021/acsami.3c16228>
6. J. S. Malhotra, M. Kubus, K. S. Pedersen, S. I. Andersen, and J. Sundberg: *ACS Sens.* **8** (2023) 3478. <https://doi.org/10.1021/acssensors.3c01058>
7. D. Wang, M. Xu, D. Zhang, Q. Mi, D. Gong, Y. Zhou, H. Wang, X. Zhang, K. Gong, and R. Zhang: *Sens. Actuators, B* **447** (2025) 138804. <https://doi.org/10.1016/j.snb.2025.138804>
8. Z. Bao, M. Aleixandre, S. Hasegawa, and T. Nakamoto: *IEEE Sens. J.* **25** (2025) 42482. <https://doi.org/10.1109/JSEN.2025.3622147>
9. T. Yamanaka, R. Matsumoto, and T. Nakamoto: *Sens. Actuators B* **89** (2003) 112. [https://doi.org/10.1016/S0925-4005\(02\)00451-3](https://doi.org/10.1016/S0925-4005(02)00451-3)
10. T. Addabbo, A. Fort, E. Landi, R. Moretti, M. Mugnaini, and V. Vignoli: *Sensors* **22** (2022) 5728. <https://doi.org/10.3390/s22155728>
11. A. Fort, E. Landi, R. Moretti, M. Mugnaini, C. Liguori, V. Paciello, and S. D. Iacono: 2024 IEEE Int. Instrumentation and Measurement Technology Conf. (I2MTC, IEEE) (2024) 1–6. <https://doi.org/10.1109/I2MTC62753.2025.11078935>
12. J.-Y. Park, R. L. Pérez, C. E. Ayala, S. R. Vaughan, I. M. Warner, and J.-W. Choi: *Electronics* **11** (2022) 358. <https://doi.org/10.3390/electronics11030358>
13. A. O. Triqadafi, T. N. Zafirah, H. A. Dharmawan, and S. P. Sakti: *J. Electr. Comput. Eng.* **2023** (2023) 5182455. <https://doi.org/10.1155/2023/5182455>
14. I. Burda: *Sensors* **22** (2022) 2337. <https://doi.org/10.3390/s22062337>
15. S. N. Songkhla and T. Nakamoto: *IEEE Sens. J.* **19** (2019) 10386. <https://doi.org/10.1109/JSEN.2019.2930733>
16. N. Gong, M. Aleixandre, and T. Nakamoto: 2022 IEEE Sensors (IEEE) (2022) 1–4. <https://doi.org/10.1109/SENSOR552175.2022.9967066>
17. H. Deng, Z. Chen, P. Feng, L. Tian, H. Zong, and T. Nakamoto: *Electronics* **14** (2025) 1852. <https://doi.org/10.3390/electronics14091852>
18. Z. Bao, M. Aleixandre, and T. Nakamoto: 2024 IEEE Sensors (IEEE) (2024) pp. 1–4. <https://doi.org/10.1109/SENSOR60989.2024.10785145>
19. M. Aleixandre, K. Nakazawa, and T. Nakamoto: *Sensors* **19** (2019) 4009. <https://doi.org/10.3390/s19184009>
20. S. Liao, P. Ye, C. Chen, J. Zhang, L. Xu, and F. Tan: *Sensors* **22** (2022) 3804. <https://doi.org/10.3390/s22103804>

Supporting Materials

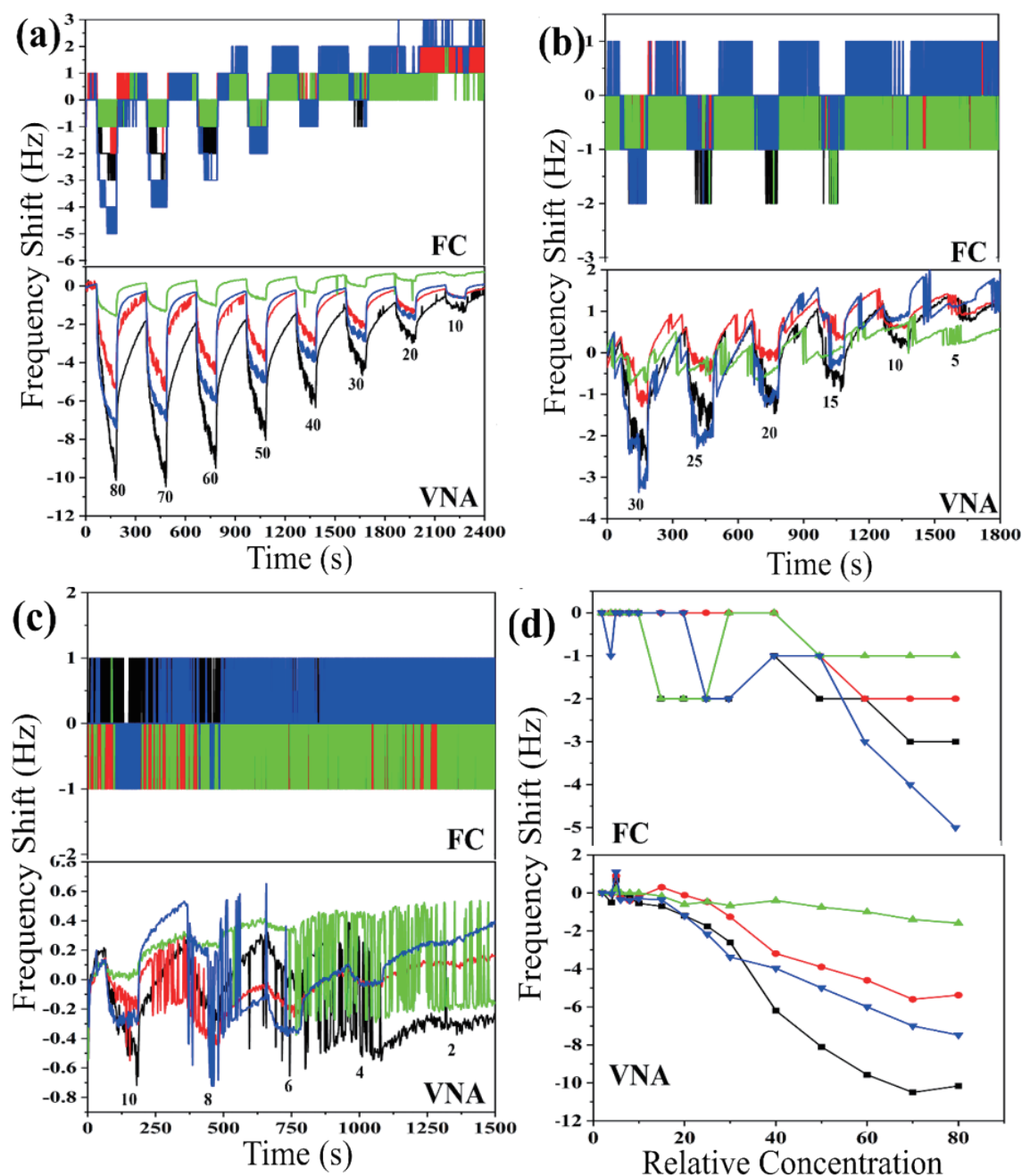


Fig. S1. (Color online) Real-time responses of all four sensors (PEG, TCEP, Thermol, and PPE sensors in black, red, green and blue, respectively) in (a) high, (b) medium, and (c) low concentration ranges of T2H as analyte gas when captured with FC and VNA-based measurement systems. (d) Sensor response versus T2H concentration plots for both FC- and VNA-based measurement systems. The value at each peak indicates concentration (%) relative to the full scale 109.8 ppm.

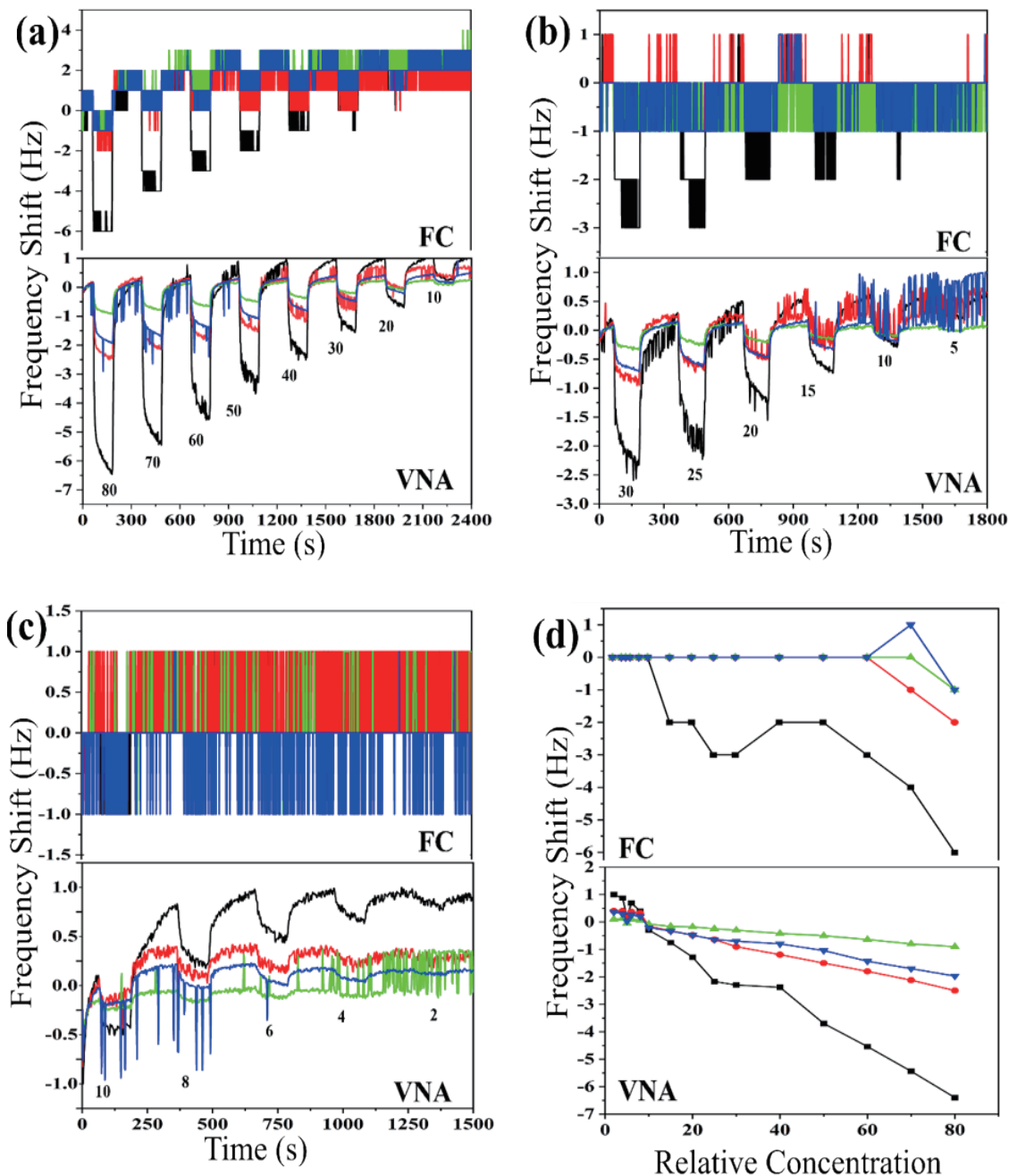


Fig. S2. (Color online) Real-time responses of all four sensors (PEG, TCEP, Thermol, and PPE sensors in black, red, green and blue, respectively) in (a) high, (b) medium, and (c) low concentration ranges of 1-B as analyte gas when captured with FC- and VNA-based measurement systems. (d) Sensor response versus 1-B concentration plots for both FC- and VNA-based measurement systems. The value at each peak indicates concentration (%) relative to the full scale 229.3 ppm.

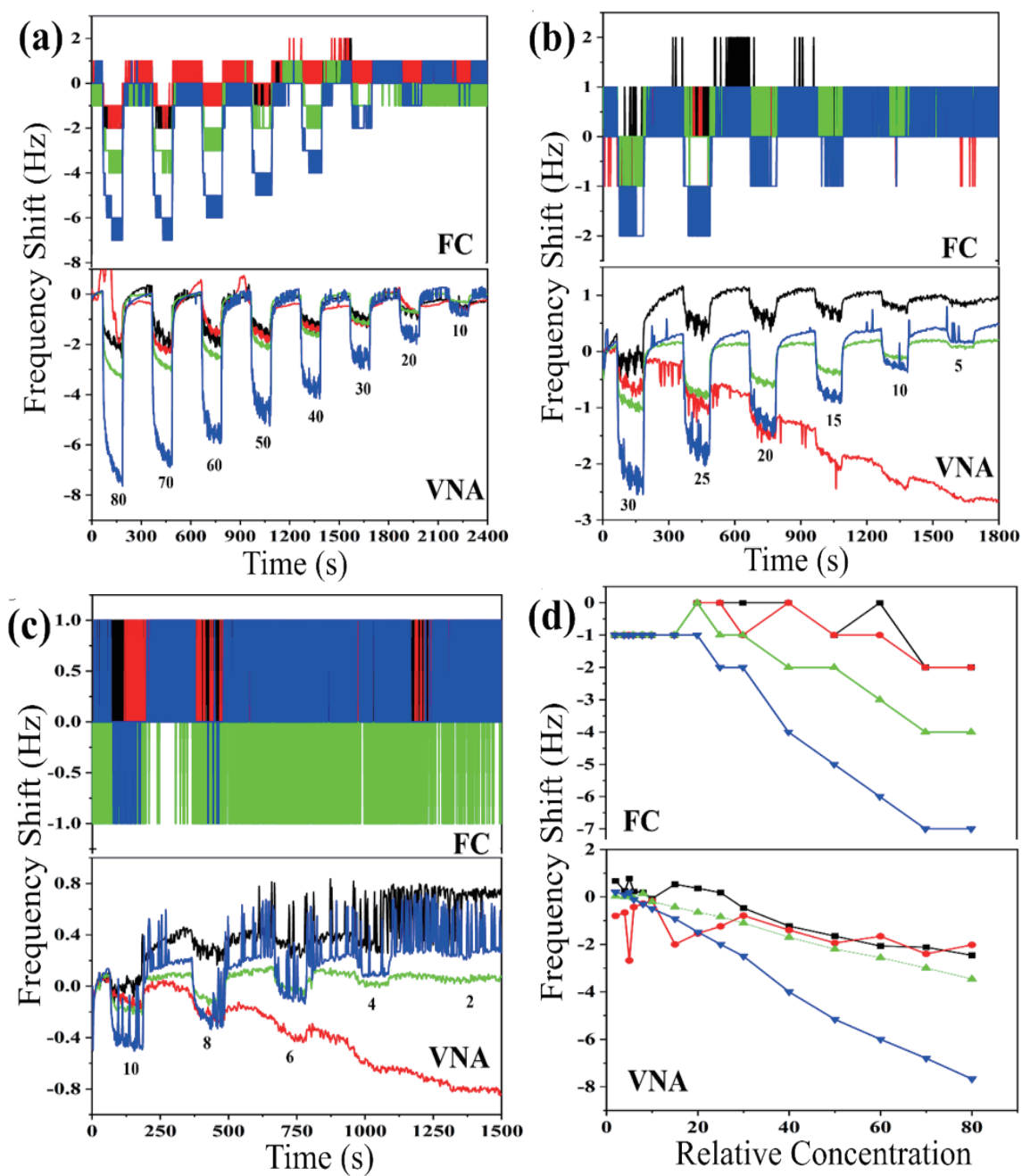


Fig. S3. (Color online) Real-time responses of all four sensors (PEG, TCEP, Thermol, and PPE sensors in black, red, green, and blue, respectively) in (a) high, (b) medium, and (c) low concentration ranges of BIB as analyte gas when captured with FC- and VNA-based measurement systems. (d) Sensor response versus BIB concentration plots for both FC- and VNA-based measurement systems. The value at each peak indicates concentration (%) relative to the full scale 45.5 ppm.