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High Performance Micro Resonators-based Sensors using Multi-Mode Excitation

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***Abstract*—We present a multi-mode excitation technique to significantly amplify the amplitude signal of micro-resonators-based sensors operating at their higher-order modes. We show that the multi-mode excitation can significantly reduce the noise effects, elevate the dynamic response level, and amplify the total amplitude response. We demonstrate the efficiency of the multi-mode excitation to enhance the performance of a gas sensor using electrothermally heated doubly-clamped buckled beams. The results indicate clear amplification for the response at the 2nd mode while detecting Helium compared to a single-source excitation. A 24-times amplitude magnification is achieved. The demonstrated approach provides a promising path to efficiently exploit the higher-order modes of resonant gas sensors leading to improved accuracy and resolution.**

***Index Terms*— Multi-mode excitation, higher-order modes, amplitude amplification, gas sensor.**

I. INTRODUCTION

A Key component of micro-electromechanical systems (MEMS) resonant sensors, micromachined resonators are extensively used in a wide range of applications [1], such as gas/mass sensing [2-3] and chemical/biological detection [4-5]. However, these sensors generally suffer from poor detection and low resolution due to the high noise floor. Thus, significant efforts have been presented to amplify their dynamic response and boost the output signal. One of the solutions that have been proposed is by adding an electrical LC tank resonant circuit [6-7]. Another approach is based on the internal resonance phenomenon [8-10], in which various vibration modes exchange energy when their natural frequencies have commensurate ratios. Parametric excitation [11-14] has also been demonstrated to boost the dynamic response of resonators [15]. However, these mentioned approaches are not so effective in activating higher-order modes, which are known to boost sensitivity and improve the performance of resonant gas sensors [16-17]. Previously [18-19], physical/chemical sensors with good response were realized when operating at the first mode. It was demonstrated that operating such sensors at the higher-order modes can lead to more improved accuracy and performance [20-21]. Hence, operating at higher order modes is a promising method to achieve high sensitivity [22-23]. However these modes are hard to excite and their response is usually buried in noise. Hence, utilizing these modes requires high input power to improve the signal readout. Thus, developing methods to amplify the higher-order modes responses is crucial for realizing ultra-sensitive resonant sensors.

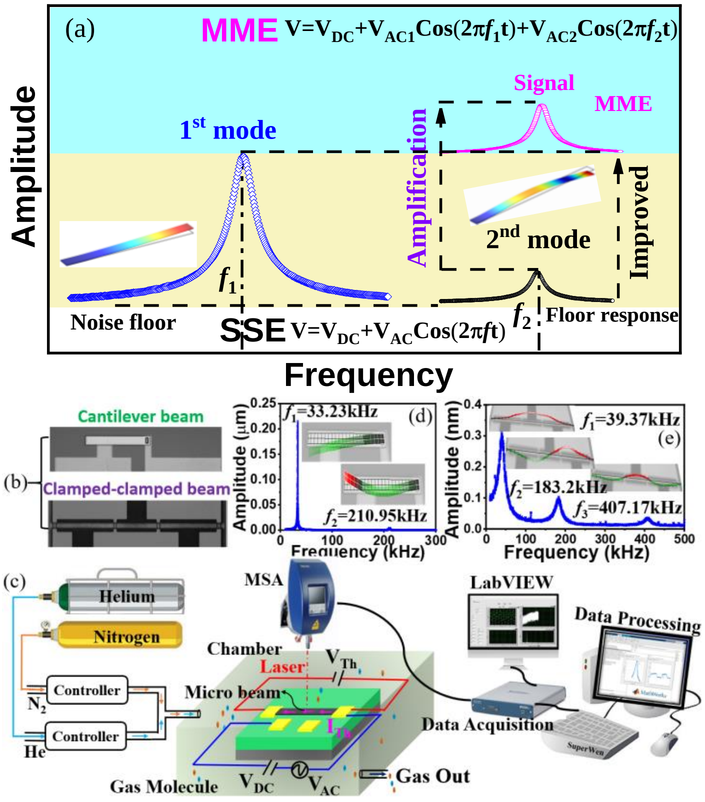

Fig. 1. (a) A schematic illustrating the advantage of the multi-mode excitation in raising the amplitude level. The tested out-of-plane resonators: (b) micro-cantilever and c-c beams. (c) Schematic of the experimental setup and gas sensing measurements. The electrothermal actuation (red) and the gas sensing setup are only used in the experiment with the clamped-clamped beam for gas sensing measurements. FFT for (d) cantilever and (e) c-c beam. Insets show the measured mode shapes.

In this letter, we present an efficient method to actuate and enhance the response of higher-order modes based on the multi-mode excitation method. The underlying principle in Fig.1a depends on the linear superposition for the dynamic response of the first two modes of the beam. The beam is excited with a DC source (V_{DC}) and two AC voltages (V_{AC1} and V_{AC2}) of two frequencies near the 1st and 2nd mode. The first mode response is strong and basically provides an elevation above the noise level. The second mode response, although weak, but is carried over the first mode response and is above the noise level. So here we take advantage of the raised elevation in response from the first mode while taking advantage of the high frequency of the second mode.

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II. DEVICE DESCRIPTION AND MEASUREMENT METHOD

We investigate micro-cantilever and clamped-clamped (c-c) micro-beams, which are actuated electrostatically into out-of-plane vibration using stationary electrodes placed underneath them. A microscopic image of the fabricated micro-beams is shown in Fig. 1b. The micro-cantilever resonator is made of polyimide and was fabricated from a six-mask surface micromachining process. It is of 275 μm length, 47 μm width, 6 μm thickness, and of a gap g separating it from the lower electrode of 2.1μm. On the other hand, the clamped-clamped micro-beam was fabricated using the MEMSCAP PolyMUMPs microfabrication process [24]. It is made of a 2 µm thick polysilicon layer with a surface of 400 × 25 μm^2 and g = 2 µm. Moreover, a stationary half-electrode configuration of thickness of 0.5 µm is deposited such that it can excite the first anti-symmetric mode of the beam.

A schematic of the measurement setup is shown in Fig.1c. It shows a Laser Doppler Vibrometer (LDV) from a Micro System Analyzer (MSA-500) of Polytec to dynamically characterize the micro resonators. In addition, a power supply and a data acquisition card (DAQ) provide AC actuation signals in a wide range of frequencies and enable recording of the output data. All devices are tested under room temperature. The cantilever micro-beam measurements are performed in low vacuum pressure of 57.8 mTorr, while those for the c-c beam have been conducted in atmospheric pressure.

The DC electrostatic load is applied to enable one-one correspondence between the excitation frequency from the power source and the one that actuates the beam (avoid exciting at double the AC frequency due to the quadratic nature of the electrostatic force). In addition, the DC load creates electrostatic force on the beam that tunes its stiffness due to its nonlinear softening effect.

Figs.1d and 1e indicate the response of the resonators due to white noise excitations where the first two out-of-plane resonance frequencies, f_1 and f_2, are found to be around 33.23 kHz and 210.95 kHz for the cantilever beam, and 39.37 kHz and 183.2 kHz for the clamped-clamped beam.

III. RESULTS AND DISCUSSION

We investigate the frequency responses of the two resonators using two methods: the single source excitation (SSE) and the multi-mode excitations (MME). To avoid the micro-beam collapse on the lower electrode (pull-in), we applied low values of DC bias voltages (i.e., 0.5V and 1.5V for the cantilever and clamped-clamped micro-beam, respectively).

Figs.2a-b illustrate the 1st and 2nd out-of-plane frequency response of the cantilever beam under the SSE. It is noted that when increasing V_{AC1} from 1V to 4 V, the amplitude of the 1st resonance response (f_1) increases from 0.149 µm to 0.751 µm, while for f_2, it increases from 0.00537 µm up to 0.02264 µm. One can clearly see that both modes show linear response under a low voltage V_{AC}=4V with a quality factor Q of 275 and 304, for f_1 and f_2, respectively. Hence, the device has higher Q at the second mode but still have a poor performance. The results at V_{AC}=4V of Fig.2b are selected as a base reference for further analysis.

Further, we show the MME results using different voltage combinations of V_{AC1} and V_{AC2} while keeping $V_{AC}=V_{AC1}+V_{AC2}$=4V, Figs.2c-d. Moreover, in the experiments, the frequency of one source is fixed near f_1 while sweeping the second one near f_2 to explore the 2nd mode response and its behaviors under different AC_1 and AC_2 combinations. We can notice from Fig.2 (b) at V_{AC}=4V, the maximum amplitude of the 2nd mode is around 0.02264 µm and the plateau of the response is close to the noise level (0.001 µm). As is observed in Fig. 2(c), a 7 times amplification is achieved after using MME and the plateau is also increased to around 0.149 µm. A similar 24 times amplitude magnification can be seen in Fig. 2(d) with V_{AC1} = 3V. Hence, a magnification amplitude mechanism of the higher order modes can be achieved with different AC_1 and AC_2 combinations.

By a closer examination, a larger AC_1 can better enhance the plateau (floor) response while the resonance peak is almost diminished, Fig. 2d. A higher frequency peak can be achieved by increasing the AC_2 source. Additionally, we found that the floor of the 2nd mode response in Fig.2c using the MME is around 0.15 µm under V_{AC1}=1V and V_{AC2}=3V. This matches with the case of V_{AC}=1V in Fig.2a using the SSE, which implies that the 1st mode response is also around 0.149 µm. These two values perfectly match. Thus, we confirm that the responses of the two simultaneously activated vibration modes are superimposed.

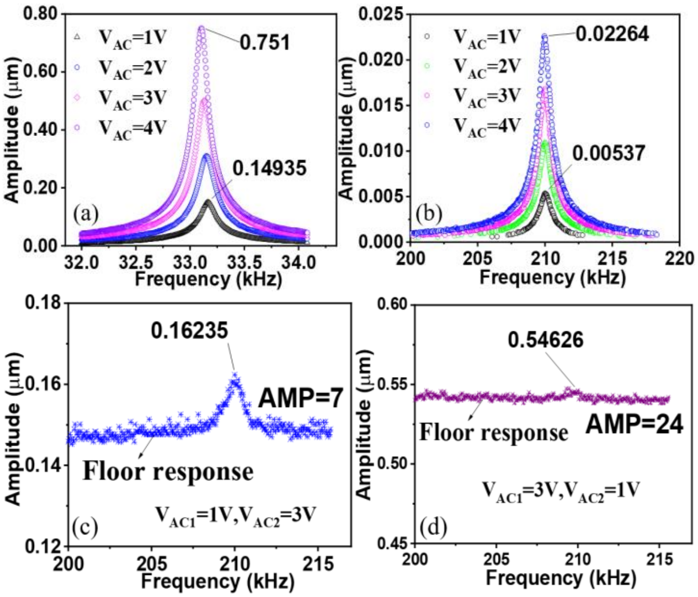

Fig 2. Cantilever beam actuated by V_{DC}=0.5V under pressure of 57.8 mTorr: (a) 1st mode; (b) 2nd mode response by single source excitation SSE; (c-d) multi-mode excitation MME response while the f_1 is fixed around 1st mode. The amplification (AMP) is defined as the ratio between the maximum amplitude of the MME to that of the SSE.

We notice that this technique can significantly enhance the floor of the 2nd frequency response from a very noisy level in the SSE. The amplitude performance can be amplified up to 10-30 times, which mainly depends on the two AC component combinations. We should mention that the proposed technique does not produce any nonlinear mode coupling and energy transfer. It only depends on the linear superposition response of the two modes. Basically, exciting the lower-order and strong mode produces the large amplitude, which boosts the weak response of the higher-order mode. Hence, the total response of both modes becomes larger, far away from the noise level.

Next, a clamped-clamped resonator is tested in Nitrogen as a reference for all the measurements in Fig.3. In the case of the SSE technique, in Fig.3a, increasing the AC sources enhances the amplitudes of the 2nd modes. The application of the MME contributes to the increase of the floor response, as shown in Fig.3b. It is noted that a higher AC_1 can better enhance the floor response, while a larger AC_2 can make the resonance peak visible and amplified, which is visible in the two case studies in Fig.3 (b). Hence, we confirm that the value of V_{AC1} dominates the 1st mode while that of V_{AC2} contributes to the response of the targeted higher order modes. Thus, increasing V_{AC1} can greatly enhance the amplification and the floor of the multi-mode response due to the two modes superposition. On the other hand, a larger V_{AC2} can make the dynamic range of the MME frequency resonance more visible.

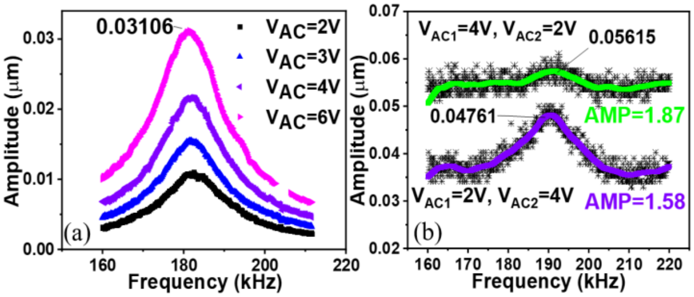

Fig 3. (a) The 2nd mode response by SSE at V_{DC}=1.5V, (b) the frequency response by MME while the f_1 is fixed around 1st mode under ambient temperature and atmospheric pressure.

We can understand the obtained results based on the mode expansion/Galerkin theorem, which expresses the beam deflection w as $w= u_1 \times \varphi 1 + u_2 \times \varphi_2$, where u_1 and u_2 are the modal amplitudes of the first and second modes, respectively, and φ_1 and φ_2, are the mode shape functions. We use u_1 to boost the total response above noise level and to help u_2, because u_2 itself is weak and within the noise level. Motivated by these results, we next apply the MME approach for gas sensing applications.

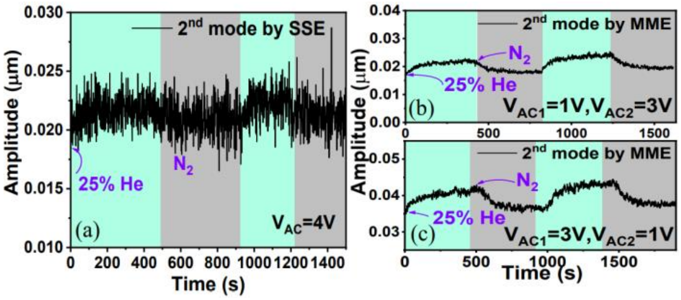

Fig 4. Real-time responses around the 2nd mode of f_2=176 kHz of the c-c resonator actuated by V_{DC}=1.5V, V_{Th}=0.28V under ambient temperature and atmospheric pressure. (a) SSE; (b) MME under V_{AC1}=1V, V_{AC2}=3V; (c) MME under V_{AC1}=3V, V_{AC2}=1V.

To explore the sensing performance, the c-c beam is placed inside a chamber, which allows different concentrations of Helium and Nitrogen through mass flow controllers. Details about the experimental setup have been reported in [18]. The proposed sensor principle is based on the cooling/heating effect between the gas molecules surrounding the electrothermally heated micro-beam [18]. For that, a DC electrothermal voltage V_{Th} is applied across the clamped-clamped beam. This induces an axial compressive force through Joule's heating, which changes the resonance frequencies, f_1 and f_2 [25].

Here, as a case study, we demonstrate the sensing of Helium. We utilize the electrothermal tuning on the resonance frequencies after the buckling point of the micro-resonator to maximize sensitivity [18]. Accordingly, the beam is operated at V_{Th}=0.28V, V_{DC}=1.5V, and V_{AC}=4V. We analyze the amplitude time response for Helium sensing. Fig.4 depicts the displacement amplitude variation results of the 2nd mode for a 25% Helium concentration for two periodic cycles. We observe that with the SSE, the displacement amplitude variation is noisy. Thus, using the 2nd mode alone is not a feasible way to sense Helium, Fig.4a. Hence, the amplitude variation response is not clear when Helium is flushed with Nitrogen, even with a higher concentration of Helium up to 25%.

However, using the MME approach with the same low voltage achieves an improved and distinct response with amplified displacement amplitude without much noise. This is shown in Figs.4b and 4c for two cases under different AC combinations. The different combinations of AC_1 and AC_2 have different performances on gas sensing, with both significantly reducing the noise effect. The increased AC_1 can substantially enhance the amplitude response due to the improved effective DC source. Thus, the amplitude displacement response of the 2nd mode can be highly enhanced using the amplification from the 1st vibration mode. These interesting results are promising for gas sensors, which can be applied to sense greenhouse gases such as CH_4, CO_2, and other toxic gases. Also, the MME technique can potentially achieve further enhancement of other higher-order modes (e.g., 3rd and 5th modes).

IV. CONCLUSIONS

This work experimentally examined the performance of MEMS resonators when excited by multi-mode excitation. We proved that the MME provides an effective way to activate the higher-order modes with amplified amplitude under a small voltage actuation compared to using a single-source excitation with the same voltage level. We found that MME can dramatically reduce the noise effects, efficiently improve the signal output, and enhance the floors of the higher-order modes response. A 24-time amplitude magnification is achieved with the MME technique. It is possible to improve this value even more with different AC combinations. Hence, it provides a practical method to activate higher-order modes (e.g. 3rd and 5th) with a magnification multiple times their amplitude to be used for resonant sensors, such as those for gas sensing. Such a promising technique with low power consumption can be an excellent candidate for other MEMS sensing applications.

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