Multi-Gas Sensing Design based on Nonlinear Coupled Micromachined Resonators

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Summary. Micro-electromechanical (MEMS) gas sensors receive increasing interest thanks to the high demand for environmental monitoring, air quality measurement, chemical process control, and personal safety. Extensive research has been conducted to improve the selectivity and sensitivity of gas sensors. However, there is still no comprehensive study on multi-gas sensing despite its potential. This work proposes a new prototype of gas sensors that can simultaneously detect the concentration of two different surrounding gases using a single structure based on a weakly coupled resonator. This study presents a thorough theoretical investigation on the dynamics of coupled cantilever and bridge resonators to prove its potential for multi-gas sensing. The sensing scheme relies on mass (due to gas absorption) and stiffness (due to cooling/heating) alteration of the cantilever and bridge resonators, respectively. A nonlinear theoretical model is developed using the Euler-Bernoulli beam theory while accounting for the geometric and electrostatic nonlinearities. The sensor's dynamic is explored using the Reduced-Order model and one-mode Galerkin discretization, showing its richness. The results suggest the potential of the nonlinear coupled resonator in performing muti-gas detection.

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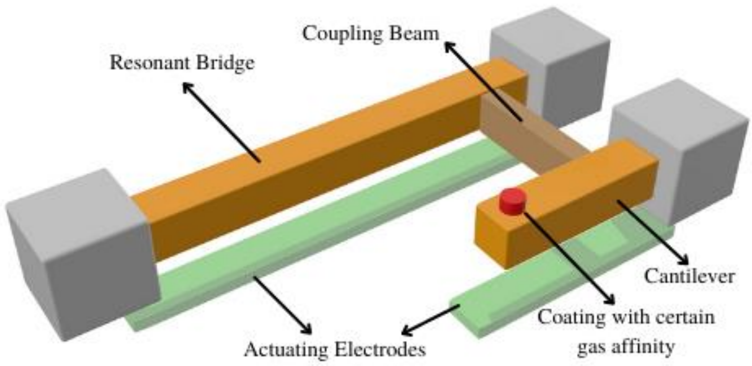
Over the past decades, several gas-sensing mechanisms have been developed, including resistive/chemical-resistive, electro-chemical, work function, thermal conductivity, optical and surface acoustic wave [1]. One of the most widely used sensor designs is based on sensors coating. These conventional gas sensors rely on special coating materials for selective and sensitive detection [2]. Alternatively, the thermal conductivity-based gas sensors show comparable sensing performance and gains lots of interests. These sensors rely on the thermal energy dissipation of a heated structure due to the alteration of the surrounding gas concentration [3]. This research will present a sensor that combines the thermal conductivity-based gas sensor technique and coating surfaces with micro-electromechanical systems (MEMS) technology. This generates a new kind of multi-gas sensing technology based on micro-gravimetric sensing by mass absorption and the thermal conductivity sensor design. The new sensing approach shows the potential to detect numerous gases and analyze the binary gas mixture.

On the other hand, electrostatically driven MEMS based mass (gas) sensors showed an excellent capability in various potential applications thanks to their easy implementation [4]. A mechanically coupled resonant device is designed to provide a stable sensing performance, as shown in Figure 1. The sensor comprises a weakly coupled resonator including a cantilever and bridge resonators. A thin coupling beam weakly couples both resonators. By changing the coupling position, the moment of inertia and the length of the coupling beam, the coupling strength could be controlled [5]. Both cantilever and the bridge resonators are driven electrostatically by a DC polarization voltage V_{DC} and an AC harmonic voltage of amplitude V_{AC}. The system geometry is optimized to ensure that both the first and second modes are similar.



Physical Parameter (Units)	Value
Gap between the electrodes of bridge, $d_1(\mu m)$	7
Gap between the electrodes of cantilever, $d_2(\mu m)$	7
Length of coupling beam, $L_c(\mu m)$	10
Length of bridge, $L_1(\mu m)$	700
Thickness of all microbeams, $h(\mu m)$	3
Widths of bridge and cantilever, $b(\mu m)$	10
Position of the coupling beam, $X_c(\mu m)$	20
Mass adsorption position, $X_m(\mu m)$	250
Bridge actuating DC voltage, V_{dc1}	50
Bridge actuating AC voltage, V_{ac1}	20
Cantilever actuating DC voltage, V_{dc2}	50
Cantilever actuating AC voltage, V_{ac2}	20

Figure 1: 3D schematic of the weakly coupled micromachined resonator for gas sensing application

Table 1: Geometric parameters of the sensor structure

The multiple gas sensing methodology is demonstrated in two aspects in this sensor structure. The bridge resonator will be heated electrothermally, experiencing convective cooling (or heating) from the ambient gas. The thermal expansion will change the bridge's stiffness and hence its resonance frequency. This technique is promised to detect gases with significant differences in thermal conductivity compared to the air (26.2 mW/mK in 300K), such as Hydrogen (186.9mW/mK in 300K) or Carbon dioxide (16.8 mW/mK in 300K) [3]. At the same time, the cantilever will be coated with a specific material having an affinity to absorb Ammonia (which has a similar thermal conductivity of 24.4 mW/mK with air), causing a mass perturbation and hence frequency shift. Through simultaneous tracking of multiple modes of vibration of the coupled resonator, the change in the surrounding gases' thermal conductivity and the mass perturbation (i.e., due to gas absorption) are shown accurately in the shift in the resonance frequency of the systems.

Results and Discussion

The analytical study is based on nonlinear Euler-Bernoulli beam theory while accounting for the geometric and electrostatic nonlinearities. To simulate the dynamics of the studied system, a reduced-order model and one-mode Galerkin discretization (for each resonator) were used. The geometric parameters of both beams are carefully designed: by adjusting the length of the cantilever, two beams' resonant frequencies are balanced (Figure 2(a)). The theoretical results of eigenvalue problems reveal how mass/stiffness perturbation influences two resonant frequencies (Figure 2(b), 2(c)). The frequency response of two beams' deflection (Figure 2(d), 2(e)) shows several non-linear phenomena of hysteresis and jumps, hence providing the possibilities of high-sensitivity sensing. The results for both stiffness and mass perturbation simulations (Figure 2(f), 2(g), 2(h), 2(i)) present rich dynamics, further prove the influence of both kinds of perturbations on resonant frequencies, which suggests the potential of the proposed design to perform multi-sensing.

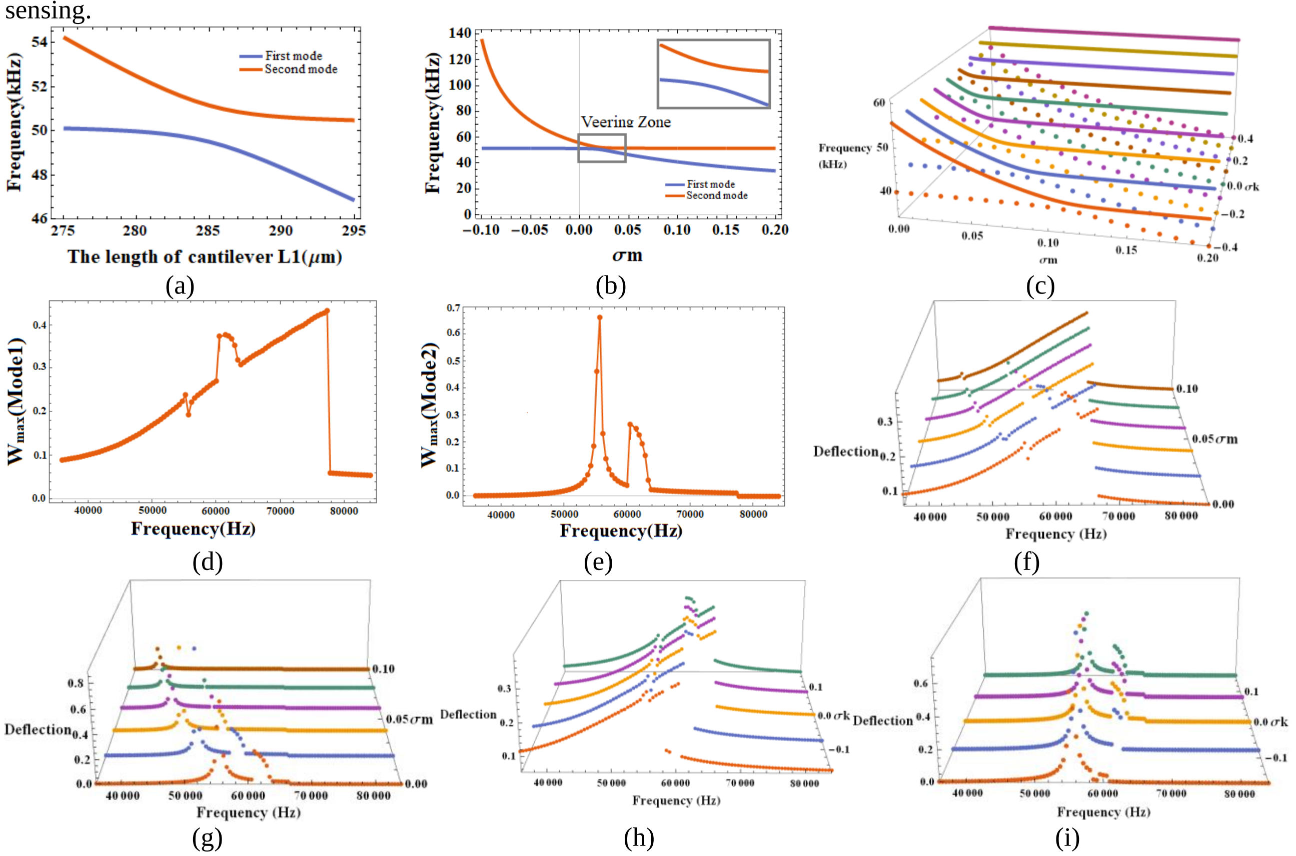


Figure 2: (a) Length of cantilever versus two resonant frequencies. Eigenvalue problems for single mass perturbation (b) and both mass and stiffness perturbation (c). The inset of (b) presents the enlarge view of veering zone.
With the actuating of $V_{dc1} = 50V$, $V_{ac1} = 20V$ on bridge resonator, the frequency response of max deflection for bridge and cantilever without perturbation (d) and (e); with mass perturbation (f) and (g); with stiffness perturbation (h) and (i).

Conclusions

We designed a potential sensor prototype for multi-gas sensing that combined micro-gravimetric sensing technique and thermal conductivity sensing techniques. The dynamics of the proposed design are simulated theoretically and showed promising results for accurate detection of two different surrounding gases simultaneously. The obtained results encourage further experimental and theoretical investigation of the dynamic of the proposed weakly coupled system. This work could reveal a new-generation answer for multi-gas sensing and show potential on different applications.

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