

Experimental realization of tunable Fano resonances in two coupled silicon micromechanical resonators

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Fano resonances originate from the interaction of a discrete state with a continuum of propagation modes. They have been observed in various quantum and classical systems. Here, we provide experimental observation of the Fano resonance in two coupled micromechanical oscillator systems. The system consists of a pair of electrostatically coupled silicon micromechanical resonators. The coupling strength between the two resonators and their stiffness can be electrically tuned. The damping of one resonator can be regulated by an external proportional feedback control system. We have achieved the switching from the Lorentzian line shape to the Fano line shape, indicating that the quality factor of the Fano resonance is more than three times that of the Lorentzian resonance. This work supplies a flexible platform for exploring the physics of Fano resonances in a mechanical system and paves the way for developing a new generation of silicon resonant sensors with superior resolution.

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I. INTRODUCTION

The Fano resonance occurs when a discrete quantum state interferes with a continuum of states [1]. It was originally regarded as a feature entirely specific to quantum systems [2]. However, wave interference phenomena are also ubiquitous in classical optics [3–5]. In particular, the asymmetric line shape of the Fano resonance promises applications for optical devices such as sensors, optical filters, switches, broadband reflectors, lasers, detectors, and slow-light devices [6–8], as well as metamaterials and metadevices [9–12]. Similarly, the Fano resonance in classical acoustics has been explored for basic physics [13,14] and sensing applications [15]. On the other hand, the Fano resonance in two weakly coupled mechanical harmonic oscillators with a periodic driving force was theoretically predicted about two decades ago [16,17], and further, the two weakly coupled mechanical harmonic oscillators are frequently utilized for illustrating the phenomena of the Fano resonance in quantum [2] and optical [5] systems. Here, we provide experimental observation of the Fano resonance in a pair of weakly coupled silicon micromechanical resonators. Our results demonstrate that resonant destructive interference can indeed be achieved by tuning the damping and stiffness of one resonator. Consequently, the basic limitations on conventional mechanical harmonic oscillators may be overcome. This work therefore has broad implications for

the physics of Fano resonances in a mechanical system and silicon resonant sensors with superior resolution.

II. AN OPERATION ANALYSIS

Figure 1 depicts a schematic of two coupled silicon micromechanical resonators. These resonators are with mass m_1 and m_2 , spring constant k_1 and k_2 , initial damping coefficient $c_1 = c_2 = c_a$, and uncoupled fundamental resonance frequency $f_0 = \omega_0/2\pi = \sqrt{k/m}/2\pi$ where ω_0 is the angular frequency, respectively. They are coupled with the coupling spring constant (k_c) between the two resonators. Different from a conventional arrangement, the coupling strength between the two resonators as well as the stiffness and damping of resonator 2 can be electrically tuned in this study.

Resonator 1 is driven by a harmonic force $f_1(t) = F_0 \cos \omega t = \text{Re}[F_0 e^{i\omega t}]$ where F_0 and ω are the amplitude and angular frequency. Applying Newton's law to the two coupled micromechanical resonators in Fig. 1 yields the following equations:

$$\begin{aligned} m_1 \frac{d^2 x_1}{dt^2} + c_1 \frac{dx_1}{dt} + k_1 x_1 + k_c(x_1 - x_2) &= f_1(t), \\ m_2 \frac{d^2 x_2}{dt^2} + c_2 \frac{dx_2}{dt} + (k_2 + \Delta k)x_2 + k_c(x_2 - x_1) &= 0, \end{aligned} \quad (1)$$

where x_1 and x_2 are the vibration displacement of resonator 1 and resonator 2, respectively. Both resonators with identical geometric dimensions were designed. Owing to fabrication tolerances, nevertheless, resonator 1 and resonator 2 are initially asymmetric. Experimentally, DC biased voltages are first adjusted so that both resonators achieve nearly the same amplitude-frequency response. As a result, both resonators are approximately considered to have the identical mass $m_1 = m_2 = m$ and the identical spring constant $k_1 = k_2 = k$. Then

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the stiffness of resonator 2 is subject to a perturbation $k_2 \rightarrow k + \Delta k = k(1 + \delta)$ where $\delta = \Delta k/k$ is the perturbation.

Taking $x_n = a_n e^{i\omega t}$ ($n = 1, 2$) for the steady-state solution, Eq. (1) is rewritten as

$$\begin{bmatrix} 1 + \mu - \lambda^2 + i\gamma_1\lambda & -\mu \\ -\mu & 1 + \mu - \lambda^2 + \delta + i\gamma_2\lambda \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix} = \begin{bmatrix} \frac{F_0}{k} \\ 0 \end{bmatrix}, \quad (2)$$

where $\mu = k_c/k$ is the coupling strength, $\lambda = \omega/\omega_0$ represents the scaled angular frequency, and $\gamma_1 = c_1/\sqrt{mk}$ and $\gamma_2 = c_2/\sqrt{mk}$ denote the loss factor of resonator 1 and resonator 2, respectively. For a system in this study, $\mu \ll 1$, $\gamma_1 \ll 1$, and $\gamma_2 \ll 1$. We make an approximation, $\lambda^2 \approx 2\lambda - 1$, $\gamma_1\lambda \approx \gamma_1$, and $\gamma_2\lambda \approx \gamma_2$. Equation (2) is then reduced to

$$\begin{bmatrix} 1 + \frac{\mu + i\gamma_1}{2} - \lambda & -\frac{\mu}{2} \\ -\frac{\mu}{2} & 1 + \frac{\mu + i\gamma_2}{2} - \lambda + \frac{1}{2}\delta \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix} = \begin{bmatrix} \frac{F_0}{2k} \\ 0 \end{bmatrix}. \quad (3)$$

Solving Eq. (3) yields

$$a_1 = \frac{1 - \lambda + \frac{\mu}{2} + \frac{\delta}{2} + i\frac{\gamma_2}{2}}{(1 - \lambda + \frac{\mu}{2} + i\frac{\gamma_1}{2})(1 - \lambda + \frac{\mu}{2} + \frac{\delta}{2} + i\frac{\gamma_2}{2}) - (\frac{\mu}{2})^2} \frac{F_0}{2k},$$

$$a_2 = \frac{\frac{\mu}{2}}{(1 - \lambda + \frac{\mu}{2} + i\frac{\gamma_1}{2})(1 - \lambda + \frac{\mu}{2} + \frac{\delta}{2} + i\frac{\gamma_2}{2}) - (\frac{\mu}{2})^2} \frac{F_0}{2k}. \quad (4)$$

The phase difference between resonator 1 and the driving signal and that between resonator 2 and the driving signal is found to be, respectively,

$$\varphi_1 = \tan^{-1} \left[\frac{\gamma_1(1 + \frac{\mu}{2} + \frac{\delta}{2} - \lambda)}{(2 + \delta - 2\lambda)(-1 + \lambda) - (2 - 2\lambda + \frac{\delta}{2})\mu} \right],$$

$$\varphi_2 = \tan^{-1} \left[\frac{\gamma_1(1 + \frac{\mu}{2} + \frac{\delta}{2} - \lambda)}{2(-1 + \lambda)(-1 + \lambda - \mu) + \delta(1 - \lambda + \frac{\mu}{2})} \right]. \quad (5)$$

The displacement of resonator 1 and resonator 2 is then written as, respectively,

$$x_1(t) = |a_1| \cos(\omega t + \varphi_1),$$

$$x_2(t) = |a_2| \cos(\omega t + \varphi_2). \quad (6)$$

From Eq. (4), the phase difference between resonator 1 and resonator 2 turns out to be

$$\theta = \tan^{-1} \left(\frac{\frac{\gamma_2}{2}}{1 + \frac{\mu}{2} + \frac{\delta}{2} - \lambda} \right). \quad (7)$$

Destructive interference occurs provided that resonator 1 is out of phase ($\theta = \pi$) with respect to resonator 2, which requires $\gamma_2 = 0$. Taking $\gamma_1 \gg \gamma_2$, the amplitude magnitude of resonator 1 can be approximately regarded as a continuum and that of resonator 2 can be approximately regarded to be discrete. The Fano resonance appears when a discrete state interferes with a continuum state [16,17]. Consequently, two weakly coupled resonators are expected to exhibit the Fano resonance when the optimal conditions are satisfied.

Letting $\gamma_2 = 0$ (it is realized by applying a feedback force in experiments) and $d|a_1|/d\lambda = 0$, one obtains a frequency

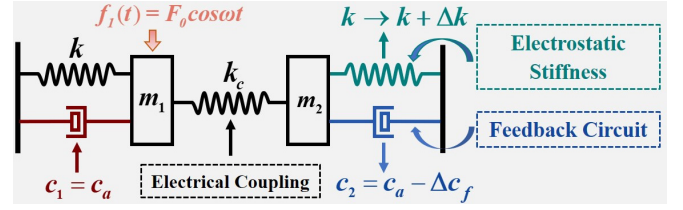


FIG. 1. Schematic of two coupled silicon micromechanical resonators represented by lumped mass (m), spring (k), damping (c). Resonator 1 is driven by a harmonic force. The stiffness and damping of resonator 2 can be electrically tuned.

at which the amplitude magnitude gets its minimum (one valley),

$$\lambda_{\min} = 1 + \frac{1}{2}\mu + \frac{1}{2}\delta, \quad (8a)$$

and a frequency at which the amplitude magnitude gets its maximum (two resonant peaks),

$$\lambda_- = 1 + \frac{1}{2}\mu + \frac{1}{4}\delta - \frac{1}{4}\sqrt{4\mu^2 + \delta^2},$$

$$\lambda_+ = 1 + \frac{1}{2}\mu + \frac{1}{4}\delta + \frac{1}{4}\sqrt{4\mu^2 + \delta^2}. \quad (8b)$$

For the two identical resonators, i.e., $\delta = 0$, it is well understood that two resonant peaks appear at $\lambda_- = 1$ and $\lambda_+ = 1 + \mu$, and the valley does at $\lambda_{\min} = 1 + \frac{1}{2}\mu$, respectively [16,17]. Resonator 1 is out of phase ($\varphi_1 = \pi$) with respect to the driving signal, leading to the valley at $\lambda_{\min}$. The amplitude magnitude as a function of frequency shows the Lorentzian line shape. Besides, the uncoupled fundamental resonance frequency and coupling strength can be extracted from two measured resonant peaks under the circumstances. Because there is a coupling between the two oscillators, the phases of both oscillators are changed when the driving frequency passes through the resonances. For $\gamma_2 = 0$ and $\delta \neq 0$, the Fano line shape appears when $\lambda_{\min}$ is adjusted to be as close as possible to λ_+ . For the two identical resonators, i.e., $\delta = 0$, this will not happen. And for $\gamma_2 \neq 0$ and $\delta \neq 0$, the Fano line shape will gradually disappear as γ_2 increases.

The aforementioned analysis can in principle account for the Fano resonance in two coupled silicon micromechanical resonators. On the basis of the equivalent circuit representation for two coupled silicon micromechanical resonators [18], we performed simulations using Advanced Design System (ADS) software to validate the analysis (see Supplemental Material S1 [19]). The results of the ADS simulation are generally in good agreement with the corresponding results predicted theoretically (Supplemental Material S2) [19].

III. EXPERIMENTAL SETUP

Experimental realization of tunable Fano resonances in two coupled silicon micromechanical resonators is shown in Fig. 2. The beam resonator with double ends clamped was used here. As indicated Fig. 2(a), the coupling between the two resonators is introduced by DC (direct current) voltage (V_{kc}) across them. When the parallel plate capacitance (C) between the two resonators separated by a small coupling gap (d) is subjected to V_{kc} , the displacement dependent

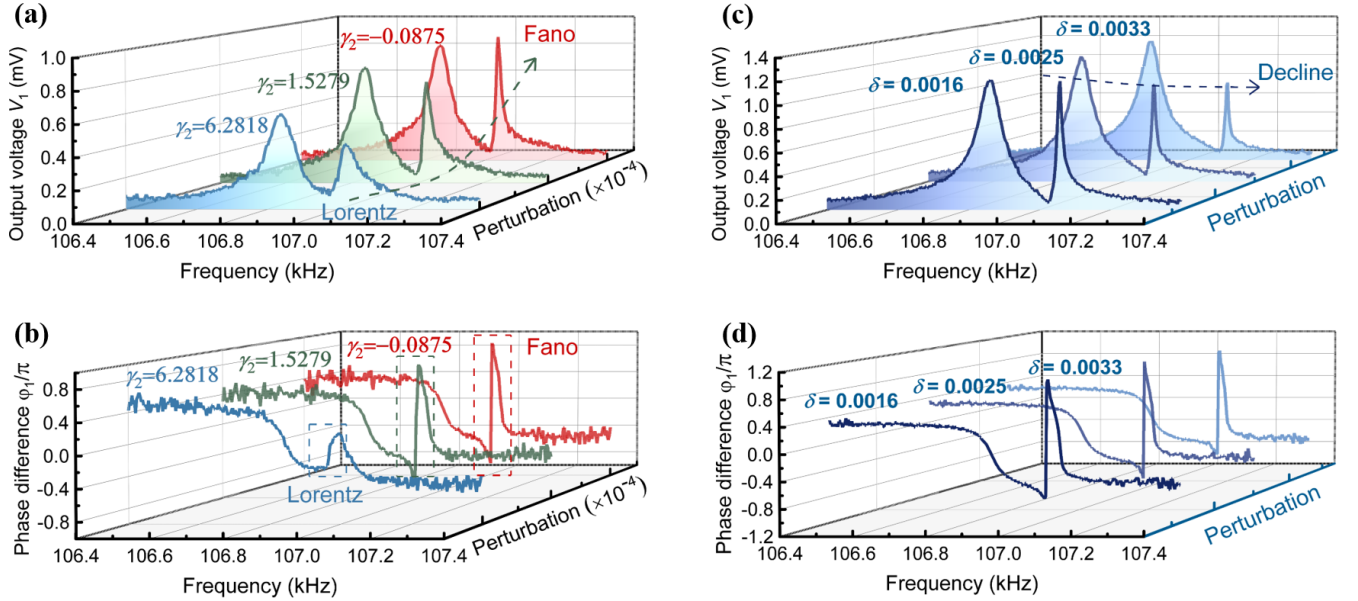


FIG. 2. Two electrostatically coupled silicon micromechanical resonators. (a) Schematic of the two coupled resonators. The beam resonator with double ends clamped was used here. The resonator is driven and sensed using parallel-plate capacitive transduction. Resonator 1 is driven by a harmonic force. The coupling spring constant can be tuned by V_{kc} . The stiffness of the resonator can be independently tuned by V_{k1} and V_{k2} , respectively. The damping of resonator 2 can be tuned by an external proportional feedback control system. It experiences successively BPF, AGC, PS, and finally, is applied back as a force to resonator 2. Sensing current due to the resonator motion is amplified by TIA and is then monitored by a lock-in amplifier. (b) Microscope image of fabricated silicon micromechanical resonators on SOI substrate.

component of the attractive electrostatic force generated between the resonators results in a mechanical-spring-like behavior. The electrostatic force is given by [20]

$$F \approx \frac{1}{2} \frac{C}{d} V_{kc}^2, \quad (9)$$

and the equivalence coupling spring constant turns out to be

$$k_c = -\frac{\partial F}{\partial d} = -\frac{CV_{kc}^2}{d^2}. \quad (10)$$

The negative effective value of the electrostatic spring represents the spring softening. Experimentally, $V_{kc} = 15$ V yielded $k_c = 0.5294$ N/m.

As indicated Fig. 2, resonator 1 and resonator 2 are biased by DC voltages V_{k1} and V_{k2} , respectively. $V_{k1} = V_{d1} + V_{ds1}$ and $V_{k2} = V_{d2} + V_{ds2} + \Delta V$ denote total DC voltages across resonator 1 and resonator 2, respectively. V_{d1} denotes the DC bias voltage across resonator 1 for driving, V_{d2} denotes the DC bias voltage across resonator 2 for the feedback driving, and V_{ds1} and V_{ds2} are the voltages across resonator 1 and resonator 2 for sensing, respectively. ΔV represents the perturbation voltage across resonator 2 for the stiffness perturbation. Likewise, the stiffness of both resonator 1 and resonator 2 can be adjusted by V_{k1} and V_{k2} , respectively [21]. V_{k1} and V_{k2} were initially adjusted so as to compensate for the slight difference between k_1 and k_2 due to fabrication tolerances. Experimentally, $V_{k1} = 54$ V and $V_{k2} = 75$ V yielded two nearly identical resonators, $k_1 = k_2 = k = 350$ N/m. The stiffness of resonator 2 was then tuned by further regulating V_{k2} (73, 71, and 69 V, respectively), and it was accordingly modified to $k_2 = k + \Delta k$ ($\Delta k = 0.56, 0.86$, and 1.16 N/m, respectively). The resonator is driven and sensed using parallel-plate capacitive transduction [22].

Both DC bias voltage (V_{d1}) and AC (alternating current) voltage ($V_a \cos \omega t$), where V_a is the amplitude, are applied to the capacitance between the driving electrode (drive) and the beam plate of resonator 1, as indicated in Fig. 2. The driving force is given by [20]

$$\begin{aligned} F &\approx \frac{1}{2} \frac{\epsilon A_{d1}}{d^2} (V_{d1} + V_a \cos \omega t)^2 \\ &= \frac{1}{2} \frac{\epsilon A_{d1}}{d^2} (V_{d1}^2 + 2V_a V_{d1} \cos \omega t + V_a^2 \cos^2 \omega t), \end{aligned} \quad (11)$$

where ϵ is the dielectric constant of vacuum and A_{d1} and d are the overlapping area and spacing between the driving electrode and the beam plate of resonator 1, respectively. In Eq. (11), the first term is a constant term, which only adjusts the equilibrium point of the resonator, the last term is high-frequency components that can be ignored, and the second term is the AC driving force as required. Then, the time-varying force applied to resonator 1 is found to be

$$f_1(t) \approx \frac{\epsilon A_{d1}}{d^2} V_a V_{d1} \cos \omega t = F_0 \cos \omega t \quad (12)$$

with $F_0 = \epsilon A_{d1} V_a V_{d1} / d^2$. Evidently, a harmonic force is obtained.

The motional displacement of both resonator 1 and resonator 2 is converted into current by using capacitive transduction. For instance, the sensing capacitance of resonator 2 is given by

$$C_{s2} = A_{s2} \frac{\epsilon}{d + x_2(t)}, \quad (13)$$

where A_{s2} and d are the overlapping area and spacing between the sensing electrode (sense 2) and the beam plate of resonator 2, respectively. From Eqs. (6) and (13), the motional current

is given by [20]

$$i_s(t) = \frac{\partial(V_{ds2}C_{s2})}{\partial t} = V_{ds2} \frac{\partial C_{s2}(t)}{\partial x_2(t)} \frac{\partial x_2(t)}{\partial t} \approx -V_{ds2}\omega \frac{\varepsilon A_{s2}}{d^2} |a_2| \sin(\omega t + \varphi_2), \quad (14)$$

where V_{ds2} is the DC bias voltage across the sensing capacitance. The motional current is then converted into output voltage by TIA (transimpedance amplifier conversion coefficient A_T):

$$V_s(t) = -V_{ds2}\omega \frac{\varepsilon A_{s2}A_T}{d^2} |a_2| \sin(\omega t + \varphi_2). \quad (15)$$

Likewise, the motional current of resonator 1 is also obtained.

The damping tuning is realized by an external feedback loop, as indicated in Fig. 2(a), where it experiences successively BPF (band-pass filter), AGC (automatic gain control,) and PS (phase shifter), and is finally applied back as a force to resonator 2. From Eqs. (6) and (15), taking the total gain (A_g) of feedback loop into account, the feedback voltage applied to resonators 2 is given by

$$v_f(t) = V_{ds2} \frac{\varepsilon A_g A_{s2} A_T}{d^2} \frac{dx_2(t)}{dt} = A_f \frac{dx_2(t)}{dt}, \quad (16)$$

where $A_f = V_{ds2}\varepsilon A_g A_{s2} A_T/d^2$. Similar to the derivation of Eq. (11), the feedback force turns out to be

$$f_f(t) = \frac{\varepsilon A_{d2}}{d^2} V_{ds2} A_f \frac{dx_2(t)}{dt} = \Delta c_f \frac{dx_2(t)}{dt} \quad (17)$$

with

$$\Delta c_f = V_{ds2}\varepsilon A_{s2} A_f/d^2,$$

where A_{s2} and V_{ds2} are the overlapping area and DC bias voltage between the driving electrode (feedback drive) and the beam plate of resonator 2, respectively. From Eq. (1), the vibration displacement of resonator 2 with the initial damping c_a under the feedback force is written as

$$m \frac{d^2 x_2}{dt^2} + (c_a - \Delta c_f) \frac{dx_2}{dt} + (k + \Delta k)x_2 + k_c(x_2 - x_1) = 0. \quad (18)$$

It can be seen that the damping of resonator 2 is adjusted to $c_2 = c_a - \Delta c_f$, where Δc_f is equivalent to the negative damping coefficient. In fact, resonator 2 has been applied by a feedback force proportional to vibration speed [23]. The negative damping coefficient can be tuned by regulating the gain of the AGC and the phase of the PS in the feedback loop. Overall, the system was designed to allow maximum tunability.

Figure 2(b) displays microscope image of fabricated silicon micromechanical resonators on SOI (silicon-on-insulator) wafers. It utilized a conventional process [24]. A pair of beam resonators with double ends clamped were electrically coupled [25]. Each of the beams in the resonators was designed 350 μm long. The length of parallel capacitive plates for coupling was designed to be 260 μm . The length of parallel capacitive plates used for driving and sensing were designed to be 200 and 260 μm , respectively. All the beams were designed to be 8 μm wide and 25 μm thick. All the capacitance spacings (d) were designed to be 2.5 μm . A

fabrication process flow is given in Supplemental Material Fig. S7 [19].

Micromechanical resonators were placed on a printed circuit board (PCB) and gold wire bonded to the metal pad on the PCB to form an electrical connection. They were then placed in a customized vacuum chamber, which was set to 170 Pa. A high-precision linear DC power supply (RIGOL DP832A and DP821A) provided DC bias (V_{kc}, V_{k1}, V_{k2}) for the micromechanical resonators and supplied power to the amplifiers. V_{kc} was initially set to be 15 V. The lock-in amplifier (Zurich HF2LI) provided frequency-sweep signal and measured the output signal. An AC voltage with the amplitude of V_a ($= 20$ mV) plus DC bias voltage V_{d1} ($= 27$ V) was applied to resonator 1 while its scanning frequency ranged 106.4–107.4 kHz. With DC bias voltage $V_{ds1} = 27$ V and $V_{ds2} = 20$ V, the TIA (Zurich HF2TA) was used to translate current into voltage for the lock-in amplifier to measure or feed into the feedback loop. Each point was sampled 20 times and then averaged to improve the accuracy by the lock-in amplifier. The photograph of the experimental setup is shown in Supplemental Material Fig. S8 [19].

IV. RESULTS AND DISCUSSION

Initially, one extracted the following parameters from the measurements: $f_0 = 106.8461$ kHz, $k_c = 0.5294$ N/m, $k_1 = 350$ N/m, $k_2 = 350.56$ N/m, $\gamma_1 = 6.4977 \times 10^{-4}$, $\gamma_2 = 6.2818 \times 10^{-4}$, and $\mu = 0.0015$, respectively. Under these circumstances, the amplitude of both resonators and the phase difference between the resonator and driving signal were observed by sequentially adjusting γ_2 , δ , and μ , respectively.

Figures 3(a) and 3(b) depict the measured output amplitude of resonator 1 and the phase difference between resonator 1 and the driving signal for different loss factors (γ_2) of resonator 2 at $\delta = 0.0016$ and $\mu = 0.0015$, respectively. For $\gamma_1 \approx \gamma_2$, two resonant peaks corresponding to $\lambda_{\mp}$ manifest as the symmetric Lorentzian line shape, and the phase difference between resonator 1 and the driving signal is approximately equal to π at the amplitude minimum, indicating that the displacement of resonator 1 is out of phase with respect to the driving signal at $\lambda_{\min}$. For a small loss factor γ_2 , the second resonant peak corresponding to λ_+ is asymmetric. As predicted by Eq. (7), for $\gamma_2 \approx 0$, resonator 1 is out of phase ($\theta = \pi$) with respect to resonator 2, and the asymmetric line shape becomes apparent at smaller loss factor γ_2 , leading to the Fano line shape. Given that the regulation of the loss factor γ_2 is achieved by an external feedback loop, the conversion of the Lorentzian line shape to/from the Fano line shape can be manipulated by switching on/off the feedback loop.

Figures 3(c) and 3(d) depict the measured output amplitude of resonator 1 and the phase difference between resonator 1 and driving signal for different perturbations to resonators 2 at $\mu = 0.0015$, $\gamma_1 = 6.4977 \times 10^{-4}$, and $\gamma_2 = 0.2911 \times 10^{-4}$, respectively. The resonant frequency (λ_+) shifts towards higher values when increasing δ , as predicted by Eq. (8b). Under different coupling strengths (μ), the output amplitude and the phase difference were also measured (Supplemental Material Fig. S4 [19]). The resonant frequency (λ_+) shifts towards higher values when increasing μ , too.

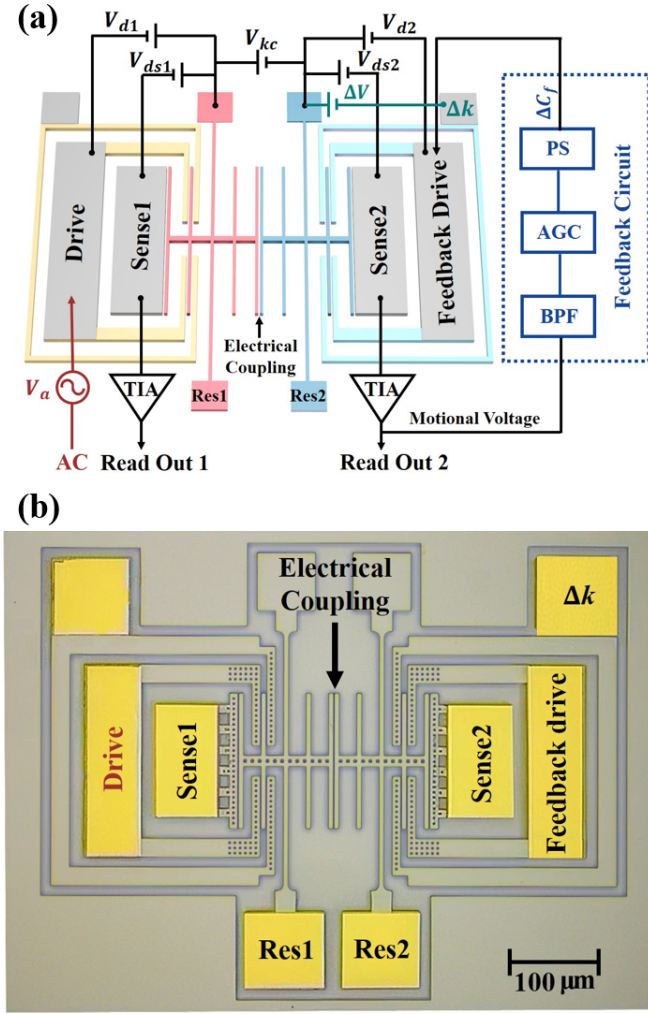


FIG. 3. Measured amplitude and phase difference as a function of frequency. (a) Amplitude of resonator 1 as a function of frequency for the different loss factors of resonator 2, $\gamma_2 = 6.2818 \times 10^{-4}$ (blue), 1.5279×10^{-4} (green), and -0.0875×10^{-4} (red), respectively. (b) Corresponding to (a), phase difference between resonator 1 and driving signal as a function of frequency. Other parameters for both (a) and (b) are $\gamma_1 = 6.4977 \times 10^{-4}$, $\delta = 0.0016$, and $\mu = 0.0015$, respectively. For $\gamma_1 \approx \gamma_2$, it displays the Lorentzian line shape, whereas for $\gamma_1 > \gamma_2$, it manifests as the Fano line shape. (c) Amplitude of resonator 1 as a function of frequency for the different perturbations to resonator 2, $\delta = 0.0016$, 0.0025 , and 0.0033 , respectively. (d) Corresponding to (c), phase difference between resonator 1 and driving signal as a function of frequency. Other parameters for both (c) and (d) are $\gamma_1 = 6.4977 \times 10^{-4}$, $\gamma_2 = 0.2911 \times 10^{-4}$, and $\mu = 0.0015$, respectively. Both (c) and (d) indicate the Fano line shape as $\gamma_1 \gg \gamma_2$. The resonant frequency (λ_+) in (c) shifts towards higher values as δ increases. The quality factor, which is defined as the resonant frequency divided by the -3 dB bandwidth, is evidently enhanced for the Fano line shape in comparison with the Lorentzian line shape.

The resonant frequency shift induced by environments is the basis of most resonant sensors. Optical sensors with high

resolution have been achieved using the ultrasharp line shape of the Fano resonance [6–8]. It is therefore significant to examine a quality factor (Q) in two weakly coupled silicon resonators. A -3 dB bandwidth method of characterizing the quality factor at λ_+ is used here. It follows from Fig. 3(a) that $Q = 2277$ for the Lorentzian line shape with $\gamma_1 = 6.4977 \times 10^{-4}$, $\gamma_2 = 6.2818 \times 10^{-4}$, and $\delta = 0.0016$, whereas from Fig. 3(c), $Q = 8235$ for the Fano line shape with $\gamma_1 = 6.4977 \times 10^{-4}$, $\gamma_2 = 0.2911 \times 10^{-4}$, and $\delta = 0.0016$. Our experimental observations clearly show that the quality factor of the resonator is substantially boosted by exploiting the very properties of Fano resonances.

As shown in Figs. 3(b) and 3(d), corresponding to the Fano line shape in the amplitude of resonator 1, the phase difference between resonator 1 and the driving signal also exhibits the Fano line shape. However, the amplitude of resonator 2 indicates the Lorentzian line shape while its phase difference exhibits the Fano line shape (Supplemental Material Figs. S5 and S6 [19]). The reason for this is that resonator 1 is out of phase with resonator 2 as λ goes through $\lambda_{\min}$ and that, at this particular frequency, the motion of resonator 1 is quenched enforced effectively by resonator 2 [16,17].

Previously, Fano resonances were observed in micromechanical systems constituted by microcantilever arrays [26]. Nevertheless, the resonant frequency and coupling strength could be only adjusted via the fabrication of various microcantilevers with different dimensions and spacing. Once they are fabricated, all cannot be regulated further. In particular, the damping difference that is dominant cannot be regulated in experiments. As a result, its asymmetric peak is even 40 dB below the Lorentz peak. Our work differs in that we aim to demonstrate the Fano resonance in two coupled micromechanical resonators, which was long predicted theoretically, and furthermore, we build a platform of manipulating the Fano resonance phenomenon.

V. CONCLUSIONS

We show experimentally the existence of the Fano resonance in two coupled micromechanical resonators. The observed effect precisely demonstrates the required interference scheme that satisfies the Fano resonance for two coupled mechanical oscillators. The capability for creating such a resonance, and for controlling the linewidth of such a resonance through tuning, is important for applications such as tunable bandwidth filters and high-resolution sensors. In addition, a fully integrated MEMS (microelectro mechanical system) platform could also be built using application-specific integrated circuits, instead of external electronic components. Our system could be of use in the manipulation of mechanical resonances, and our work opens up an avenue for developing a next generation of filters and sensors in silicon technology.

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