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Counter operation in nonlinear micro-electro-mechanical resonators

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ABSTRACT

This Letter discusses a logical operation of multi-memories that consist of coupled nonlinear micro-electro-mechanical systems (MEMS) resonators. A MEMS resonator shows two coexisting stable states when nonlinear responses appear. Previous studies addressed that a micro- or nano-electrical-mechanical resonator can be utilized as a mechanical 1-bit memory or mechanical logic gates. The next phase is the development of logic system with coupled multi-resonators. From the viewpoint of application of nonlinear dynamics in coupled MEMS resonators, we show the first experimental success of the controlling nonlinear behavior as a 2-bit binary counter.

1. Introduction

A micro-electro-mechanical resonator is a kind of devices fabricated using micro-electro-mechanical systems (MEMS) technology. A MEMS resonator substantially shows nonlinear responses at large excitation force. The dynamics of a nonlinear micro- or nano-electro-mechanical resonator is described by the Duffing equation [1–6]. At nonlinear responses, an amplitude–frequency response curve bends toward higher or lower frequencies due to a hard or soft spring effect [7]. In particular, at a fixed excitation frequency in the hysteresis region, a nonlinear MEMS resonator has two stable periodic states and an unstable periodic state [8].

Recently, many studies focus on mechanical computation especially in micro- and nano-electro-mechanical resonators [1,3,6, 9–16]. A mechanical memory device is a prospective application of nonlinear micro- or nano-electro-mechanical resonators [1,3, 6,9–12]. Previous studies demonstrated that a micro- or nano-electro-mechanical resonator can be applied to execute mechanical logic gates [13–16]. It is natural to expect that the next phase is the development of logic system with coupled multi-resonators.

This Letter discusses a 2-bit binary counter [17] from the viewpoint of application of nonlinear dynamics in coupled MEMS memories. The authors experimentally showed the switching control between two coexisting stable states at a fixed excitation frequency in a nonlinear MEMS resonator [11]. Based on our previous study, here we show the first experimental success of the controlling nonlinear behavior in two coupled MEMS resonators as a 2-bit binary counter.

The overview of this Letter is organized as follows. Section 2 presents two fabricated MEMS resonators and its four coexisting stable states. Section 3 explains the switching control system in the coupled nonlinear MEMS resonators. In Section 4, the switching control sequence of counter operation is experimentally achieved and examined.

2. MEMS resonator and its coexisting stable states

Fig. 1 shows an electrostatically driven comb-drive resonator that was fabricated with silicon on insulator (SOI) technology [4, 18,19]. When a MEMS resonator is actuated by applying an ac excitation voltage with a dc bias voltage between the mass and the electrodes, the mass vibrates in the X-direction with a weak link to the Y-direction. In this Letter, we utilize two comb-drive resonators.

Fig. 1 also presents a schematic diagram of the experimental setup in the differential measurement [20] for a single MEMS resonator as described in Ref. [11]. In the differential measurement for a single MEMS resonator, excitation force F_j and output voltage $V_{\mathrm{out}j}$ are obtained by the following equations:

$$F_j = 4\varepsilon N \frac{h}{d} V_{\mathrm{dc}j} v_{\mathrm{ac}j} \sin 2\pi f_j t, \tag{1}$$

$$V_{\mathrm{out}j} = 8 \times 10^8 \pi f_j \varepsilon N \frac{h}{d} v_{\mathrm{ac}j} A_j \sin(4\pi f_j t + \phi_j), \tag{2}$$

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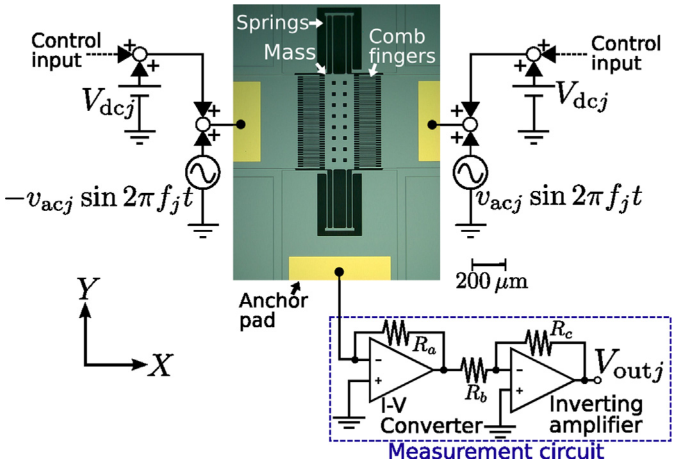
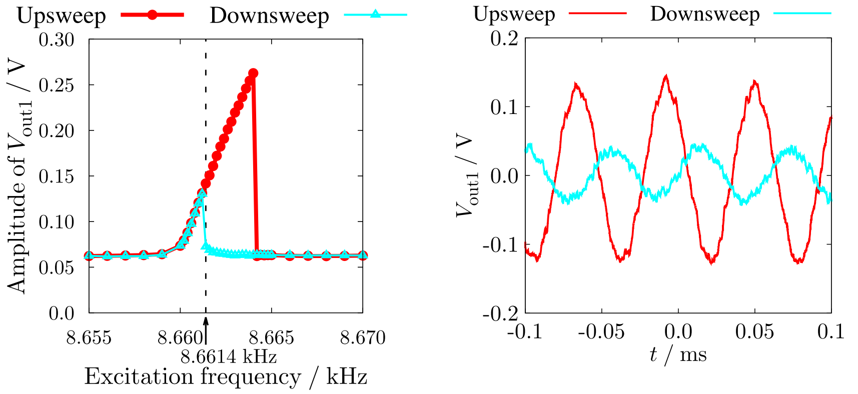


Fig. 1. Schematic diagram of single comb-drive resonator and measurement system. Fabricated resonator has a perforated mass with length, width and thickness of 575, 175 and 25 μm. The perforated mass is supported by folded beams, which are used as springs. They are connected to anchors. The MEMS resonator has two comb capacitors. Resistors R_a, R_b, and R_c are set at 1 MΩ, 1 kΩ, and 100 kΩ. Output voltage $V_{\mathrm{out}j}$ depends on the amplitude and the phase of the displacement.

where $j = 1, 2$. Here f_j denotes the excitation frequency of the j-th MEMS resonator in the coupled system, A_j the amplitude of the displacement, and ϕ_j the phase. N $(= 39)$ denotes the comb number of each resonator, h $(= 25\ \mu\mathrm{m})$ the finger height, d $(= 3\ \mu\mathrm{m})$ the gap between the fingers, and ε $(= 8.85 \times 10^{-12}\ \mathrm{F/m})$ the permittivity. We set the dc bias voltage $V_{\mathrm{dc}j}$, the ac excitation amplitude $v_{\mathrm{ac}j}$, and the pressure at -0.15 V, 0.6 V, and around 12 Pa at room temperature. The first (second) MEMS resonator is called Res. 1 (Res. 2) from here on.

Fig. 2(a) (3(a)) shows the experimentally obtained frequency response curves in Res. 1 (Res. 2). The red and aqua lines correspond to the responses at the upsweep and the downsweep of frequency, respectively. The frequency response curves strongly depend on the sweep direction in the hysteresis region. We found that the behavior exhibited by the MEMS resonator qualitatively resembles to each other. Two stable states coexist at $8.6612\ \mathrm{kHz} < f_1 < 8.6642\ \mathrm{kHz}$ in Fig. 2(a) and at $8.6134\ \mathrm{kHz} < f_2 < 8.6162\ \mathrm{kHz}$ in Fig. 3(a). It was considered that the difference of hysteresis is caused by different doping angle, debris deposited during fabrication and die separation, and/or minute cracks [18].

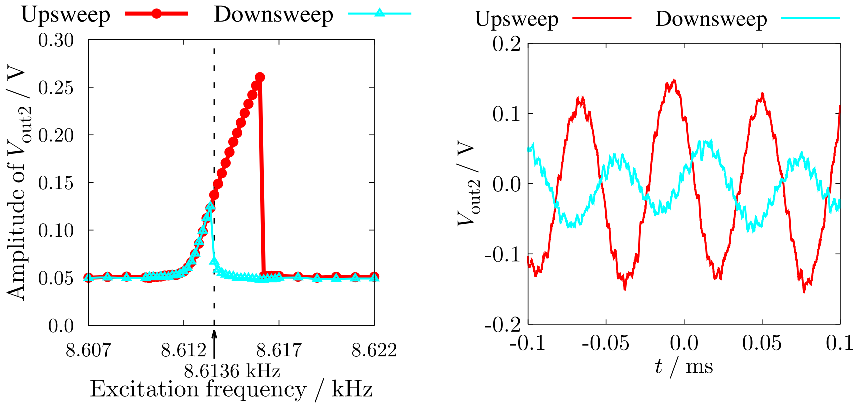
Figs. 2(b) and 3(b) show the oscillogram of two stable periodic vibrations at 8.6614 kHz in Res. 1 and at 8.6136 kHz in Res. 2. The red and aqua lines are averaged out over 32 measurements.



(a) Amplitude-frequency response curves of Res. 1.

(b) Two coexisting stable states at $f_1 = 8.6614\,\mathrm{kHz}$ of Res. 1.

Fig. 2. Displacement measurement by differential configuration in Res. 1. At any given frequency in the hysteretic regime, the resonator can exist in two distinct amplitude states. (For interpretation of the references to color in this figure, the reader is referred to the web version of this Letter.)



(a) Amplitude-frequency response curves of Res. 2.

(b) Two coexisting stable states at $f_2 = 8.6136\,\mathrm{kHz}$ of Res. 2.

Fig. 3. Displacement measurement by differential configuration in Res. 2. Two different vibrational states coexist. (For interpretation of the references to color in this figure, the reader is referred to the web version of this Letter.)