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Electrothermally actuated tunable clamped-guided resonant microbeams

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ABSTRACT

We present simulation and experimental investigation demonstrating active alteration of the resonant and frequency response behavior of resonators by controlling the electrothermal actuation method on their anchors. In-plane clamped-guided arch and straight microbeams resonators are designed and fabricated with V-shaped electrothermal actuators on their anchors. These anchors not only offer various electrothermal actuation options, but also serve as various mechanical stiffness elements that affect the operating resonance frequency of the structures. We have shown that for an arch, the first mode resonance frequency can be increased up to 50% of its initial value. For a straight beam, we have shown that before buckling, the resonance frequency decreases to very low values and after buckling, it increases up to twice of its initial value. These results can be promising for the realization of different wide–range tunable microresonator. The experimental results have been compared to multi-physics finite-element simulations showing good agreement among them.

1. Introduction

Microelectromechanical systems (MEMS) resonators have been investigated widely for many applications owing to their advantages of small size and high sensitivity. MEMS resonators can be employed for frequency specific applications, such as oscillators [1,2], filters [3,4], energy harvesting [5,6], and logic gaits [7]. They are typically actuated using various transduction techniques including magnetic [8], electrostatic [9], and electrothermal [10,11]. Electrostatic and electrothermal actuators are commonly used for their simplicity and the fact that they can generate larger deflection and forces [12,13]. Both techniques can be used for tuning the resonance frequency through the application of a DC actuation voltage [14].

Electrostatic actuation is widely used for MEMS resonators due to the low power consumption; however they suffer disadvantages, such as the high DC actuation voltage [13]. Electrothermal actuation provides wide resonance frequency tuning with low operating voltages. Its advantages include the simplified fabrication and the high force actuation [15–17]. Several electrothermal actuation techniques have been developed for frequency tuning of resonators. They all rely on the resistive heating, which is based on inducing thermal strain from the thermal expansion of structures caused by Joule's heating [17–19].

Many types of electrothermal actuators have been explored, such as U-shapes structures [20,21], V-shaped or Chevron shaped beams [15–22], Z-shapes structures [23,24], and clamped–clamped straight or arch beams structures [25,26]. The V-shaped structure has been widely used due to its high force (in the order of mN) and reasonable displacement (a few

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μm) [15]. However, this structure may have large stiffness, which limits their actuation range [24]. Additionally, electrothermal tuning using clamped-clamped beams and arches were demonstrated, such as the work of Jun et al. [27] who used the electrothermal tuning on a doubly-clamped beam structure to tune the resonance frequency up to 10%.

The effect of the elasticity of the anchors on the behavior of microstructures has been also studied. Alkharebshah and Younis [28] studied the effect of the flexible support on the dynamics behavior of electrostatically actuated MEMS arch beams. Chen et al. [29] discussed the bifurcation analysis problem of an arch structure with parametric and forced excitation with an elastic boundary supporting stiffness.

In a previous work [30], we utilized the electrothermal actuation to tune the resonance frequency of a clamped-clamped microbeam resonator through passing a DC current through it. The resonance frequency has been shown to be increased up to twice of its initial value. Such designs however suffer the limitation coming from heating the anchors of the beams, which make them vulnerable to damage and make devices less reliable.

Many MEMS applications need high frequency tuning for filtering [31] and logics [7] applications. In this paper, we demonstrate highly tunable in-plane electrothermal actuators with the flexibility of shifting and choosing the operating frequency range upon demand. Two structures of V-shaped beams and clamped–guided shallow arch beam are chosen to demonstrate wide range of tunability. We prove various ways of obtaining high tunability of a structure by controlling the electrothermal actuation method on the anchors of the V-shape beams.

2. Design and device principle

Resonators have been designed as clamped-guided microbeams with electrothermal actuators of V-shaped structures on the sides, Fig. 1. The basic unit of the V-shaped structures is a pair of inclined beams and a shuttle in the middle. A schematic illustrating the mechanical effect of the V-shaped structures is shown in Fig. 2, where each V-shape structure consisting of two pairs of electrothermal beams of stiffness elements denoted by K_A, K_B, K_C, and K_D.

Applying a voltage across the two anchors of the V-shaped structure generates heat across it due to Joule's heating. In the V-shaped actuator, the temperature expands the beams and moves the shuttle in the positive x–direction, and hence generating compressive axial loads on the clamped-guided microbeams. These compressive forces change the stiffness of the clamped-guided beams, which for the straight configuration means decreases in their stiffness and resonance frequencies until the buckling limit and for the initially curved beams (arches) increase in their curvature (displacement in the y-direction), stiffens, and hence their resonance frequencies [30,32].

As shown in Fig. 2, there are four actuation pads labeled A, B, C, and D, which offer five different ways of electrical connections, and hence electrothermal actuation. First is between A and B (Case A), second is between C and D (Case B), third is between A and D (Case C), fourth is between C and B (Case D), and the fifth is between A and B where there are a connection between A and C, and B and D (Case E), as depicted in Fig. 2. To avoid the rotation of the structure in the y-z plane, the guided structure is suspended with two flexure beams. Two-different architectures of clamped-guided microbeams are designed for the experimental work: straight and shallow arch beams.

The resonators are fabricated from a highly conductive silicon device layer of silicon-on-insulator (SOI) wafer from MEMSCAP [33]. Fig. 3 shows a picture of one of the fabricated resonators with clamped-guided beams. The beams are of 800 μm and 1000 μm in length (L), 2.5 μm in width (h), and 25 μm (Si device layer of SOI wafer) in thickness. The gap

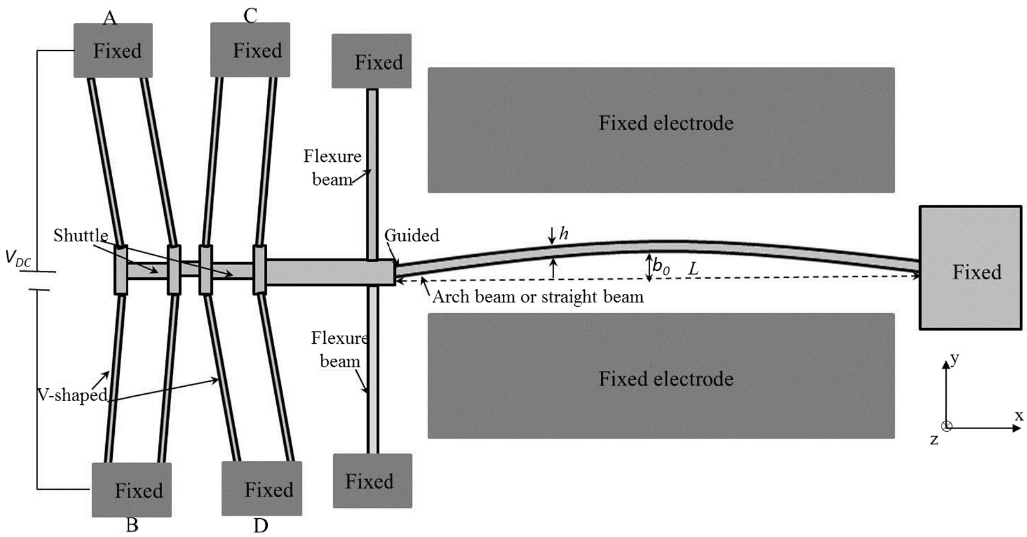

Fig. 1. Schematic of the resonators. A fixed-guided microbeam suspended by two V-shaped structures with electrothermal actuation.