MULTI-FUNCTION AND CASCADABLE MEMS LOGIC DEVICE

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ABSTRACT

We present a reprogrammable Microelectromechanical systems (MEMS) logic device that can perform the fundamental logic gate AND, a universal logic gate NAND, and a tristate logic gate using mixed-frequency excitation. The concept is based on exciting combination resonances due to the mixing of two or more input signals. The device vibrates at two steady states; a high state when the combination resonance is activated and a low state when no resonance is activated. These vibration states are assigned to logical value 1 or 0 to realize these logic gates. Using AC signals to drive the resonator and to execute the logic inputs unifies the input and output wave forms of the logic device, thereby opening the possibility for cascading among logic devices. Moreover, the ability to perform these logic operations at any input frequency using frequency mixing techniques allows for overcoming the limitation of having a fixed operating frequency. These characteristics of such logic devices lay down the basis to achieve complex computing operations.

INTRODUCTION

Recently, computing through MEMS/NEMS (Nano) devices has garnered considerable attention as they provide single active structures capable of performing multiple logic operations. These logic devices provide advantages, such as low power consumption, high integration densities, and harsh environment operation over CMOS based technologies [1].

Switch based MEMS/NEMS logic devices have been demonstrated capable of performing multiple logic operations using a single structure [2, 3]. These devices however have limitations in practical application due to wearing of the contacting surfaces over time, in addition to other stiction and friction issues [4]. To overcome this drawback, recent research has focused on noncontact based micro computing using MEMS/NEMS resonators [5-10]. These use two different vibration states of a resonator as the logical values 1 and 0. The first dynamics based logic device utilized piezoelectric NEMS structure to perform XOR operation [5]. Later, a reprogrammable nanomechanical logic gate was demonstrated capable of performing the AND/OR gates and their complements [6]. The device operates in the nonlinear regime and utilizes the hysteric bistable region near resonance to perform the logic operations. Logic operation also based on the activation of different modes of a membrane resonator has been demonstrated [7]. Recently, a rather unconventional reversible logic gate (Fredkin gate) has been demonstrated via four coupled resonators [8]. Furthermore, universal logic devices capable of performing all the logic gates have been demonstrated utilizing the principles of parametric resonances [9] and thermal modulation of frequencies [10].

Resonator based logic devices provide a great advantage since they are non-contact devices. However, they have strict operating conditions of requiring a fixed operating frequency. Moreover, the resonator based logic devices demonstrated so far [5-10] utilize different input (DC) and output (AC) signals. These factors make cascading these gates challenging and add additional complexity to the circuit. In this work we present a cascadable logic device resonator having similar AC signals at the input and output, capable of performing AND/NAND logic operations at any input frequency based on frequency mixing techniques [11]. The device is also capable of performing a tristate logic operation using similar frequency mixing.

METHODS AND MATERIALS

Design and Fabrication

The experimental logic device comprises of a clamped-clamped microbeam of length 500 µm, width 50 µm, and a nominal thickness of approximately 7 µm fabricated via a surface micromachining process using polyimide as the structural layer [12]. A Laser Doppler Vibrometer is used to record device maximum amplitude of vibration [13]. The device works in the linear regime where the activation and deactivation of combination resonances define the vibrational states required to perform the different logic operations.

Mixed-Frequency Excitation

To demonstrate frequency mixing as a viable technique to perform reprogrammable and cascadable MEMS logic operation, the dynamic behavior of the microbeam under a two source excitation is first demonstrated and compared against the single source excitation. To drive the microbeam under a single source excitation, the microbeam is subjected actuated by a DC voltage source superimposed to an AC voltage source with the frequency swept around the primary resonance. The numerator of the electrostatic force term applied on the microbeam can be expressed as

$$\left[V_{DC}+V_{AC}\cos(\omega)\right]^2 \tag{1}$$

In case of a two-source excitation, the microbeam is subjected to a single DC voltage source and two AC voltage sources. One of the AC sources is applied at a fixed frequency while the other one is swept over a certain range. The numerator of the electrostatic force term in this case is given by

$$\left[V_{DC}+V_{AC1}\cos(\omega_1)+V_{AC2}\cos(\omega_2)\right]^2 \tag{2}$$

By expanding (2) we get

$$\begin{aligned}&V_{DC}{}^2+V_{AC1}{}^2.\cos^2(\omega_1 t)+V_{AC2}{}^2.\cos^2(\omega_2 t)\\&+2V_{DC}.V_{AC1}.\cos(\omega_1 t)+2V_{DC}.V_{AC2}.\cos(\omega_2 t)+\\&V_{AC1}.V_{AC2}.[\cos\{(\omega_1-\omega_2)t\}+\cos\{(\omega_1+\omega_2)t\}]\end{aligned} \tag{3}$$

It is noticed from the last term of (3) that mixing two AC sources gives birth to two new resonances called combination resonances [11]. An additive type resonance appears when the sum of the fixed frequency (ω_1) and variable frequency (ω_2) equals the natural frequency (ω_n) of the system, i.e. $\omega_1+\omega_2=\omega_n$, where a subtractive type resonance appears when the difference of the fixed frequency and the variable frequency equals the natural frequency of the system, i.e. $\omega_1- \omega_2=\omega_n$.

Figure 1a shows the experimentally obtained response of the microbeam under a single source excitation (red) and a multi-source excitation (blue). An additive type resonance appears when the sum of the fixed frequency (ω_1=2 kHz) and the variable frequency (ω_2=124 kHz) equals the natural frequency (ω_n=126 kHz) of the beam, whereas a subtractive type resonance appears when the difference of the fixed frequency (ω_1=2 kHz) and the variable frequency (ω_n=128 kHz) equals the natural frequency of the beam. These combination resonances can have amplitude as high as the amplitude at primary resonance and can be shifted to any frequency through adjusting the input signal parameters.

MEMS Logic Operation

The activation of the combination resonances in the linear regime is utilized here to perform the logic operation. The additive type combination resonance is selected here to demonstrate logic operations. Contrary to the state of the art, an AC input signal is used here to execute the logic operations, which gives the potential to cascade these logic devices by having similar forms of input and output signals. Furthermore, this allows control over an extra parameter, i.e., the frequencies associated with the input AC voltages, which in turn enables the logic device to work at any given frequency by adjusting the input signals. For instance, if one of the frequencies is fixed at 94 kHz, then in order to activate the additive type resonance the other mixing source must be set at 32 kHz, since the sum of these two mixing frequencies leads to 126 kHz (primary resonance frequency). Figure 1b shows the amplitude response for this excitation. Assuming the operating point for the logic gate in this case is at 32 kHz, we can classify the two vibration states of the microbeam at this point as the two logic states (1/0 and 0/1).

Figure 2 shows the operation of an AND/NAND gate using the mixed-frequency excitation. The two frequencies associated with the input voltages are 94 kHz and 32 kHz. It is noteworthy here that any of these frequencies can be the operating point of the logic gate. Whenever both of these inputs are on, only then the condition for the activation of combination resonance of additive type is true and the resonator vibrates with increased amplitude. In all other cases the microbeam does not experience any resonance and hence shows negligible vibration. Depending on the assignment of the logical value to these two vibration states of the resonator, an AND (blue) or an NAND (red) gate is realized.

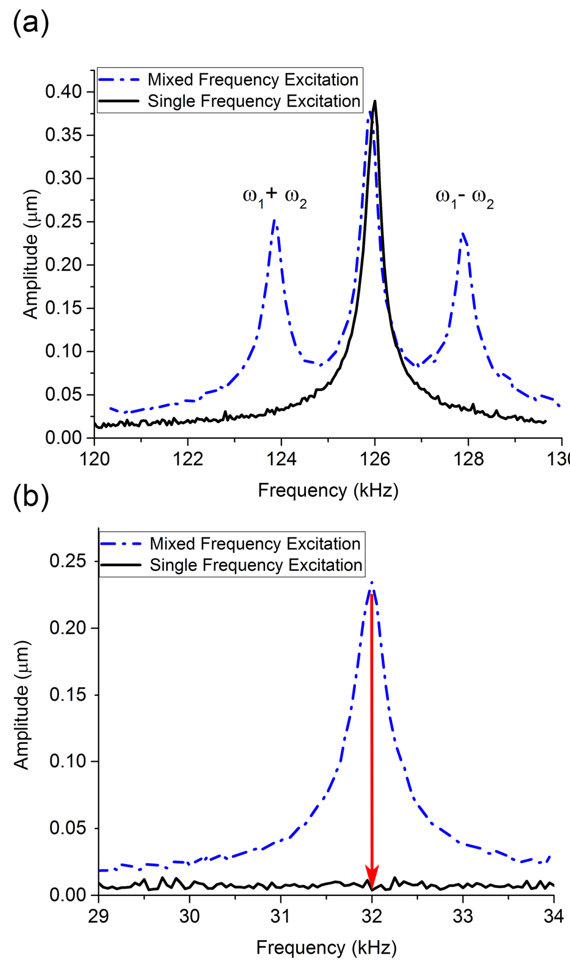
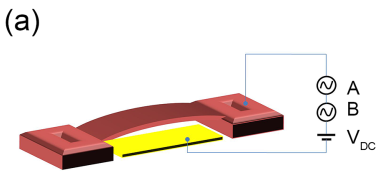


Figure 1: (a) Response of the microresonator at V_{DC}=2V, V_{AC}=2.5V for a single frequency excitation (solid). Multi-frequency excitation (dashed) at V_{DC}=2V, V_{AC1}=2.5V, and V_{AC2}=2.5V at 2 kHz. Combination resonances are activated at 124 kHz (additive) and 128 kHz (subtractive). (b) The response without mixing (solid) and with mixing (dashed). Fixed-frequency=94 kHz for multi-source excitation. The low and high vibrations states at 32 kHz are assigned the two logic states 0/1or 1/0 for AND/NAND operation, respectively.

Next, a special purpose tristate logic gate, Figure 3, is realized via the mixing of three sources. This gate acts as a valve in electronic circuits, i.e., when the control input is "ON" the input transfers to an output otherwise it assumes a "hi-Z state". This tristate logic or buffer is also one of the basic and essential elements in basic computing units. A constant activation input source "V_A" at 32 kHz is applied to the resonator at all times. The input signal "In" is applied also at 32 kHz, whereas the control input "C" is applied at a fixed frequency of 94 kHz. When the control signal is off (0) the combination resonance can never be activated as the mixing sources do not fulfill the conditions for the activation of combination resonances of any type. The resonator vibrates with negligible amplitude and this state is referred to as high impedance (Z). Next, when the control "C" is on (1) and the input "In" is off (0) there is mixing due to the presence of the activation input “V_A” between “C” and “V_A”. As programmed this specific mixing activates the additive type combination resonance and a high vibration state is achieved. This vibration level defines the “0” state for the tristate logic gate. Finally, when the control “C” is on (1) and the input “In” is also on (1), there is mixing among all the input signals. An additive type resonance is activated due to the mixing between input “V_A” and control “C” and another additive type resonance is activated due to the mixing between input “V_A” and input “In”. Since both of these resonances are activated at the same operating point, the amplitude adds up and results in a much higher vibration state referred to as “1” state for the tristate logic.

(a)



(b)

A	B	AND	NAND
0	0	0	1
0	1	0	1
1	0	0	1
1	1	1	0

(c)

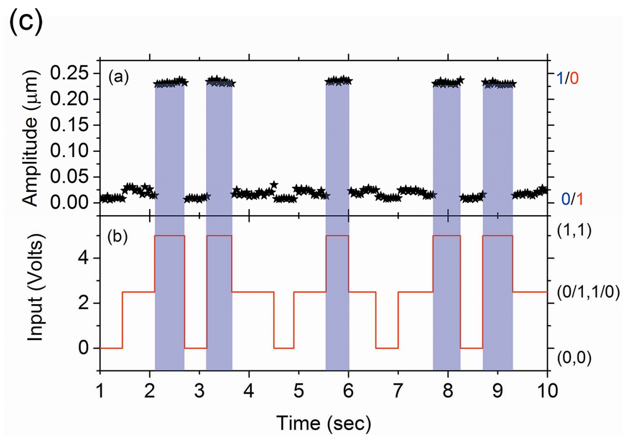
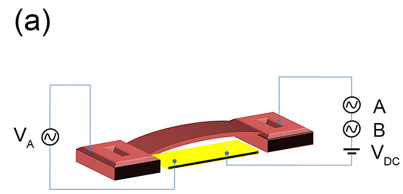


Figure 2: Demonstration of an AND/NAND gate. (a) Microresonator electrical interconnects. (b) Truth table for AND/NAND logic device. (c) The maximum response of the microbeam versus time for all the input logic states. The two frequencies associated with the input voltages are 94 kHz and 32 kHz.

RESULTS AND DISCUSSION

The proposed device in its current form occupies an area of ~3.2x10^5 μm^2 including electrodes and anchors. This provides the device with an integration density of ~10^3. The theoretical open loop operating speed of the device is found to be, f/Q~200Hz, where f is the resonance frequency and Q is the quality factor [10]. Another important performance parameter is the energy consumed during the operation, which is calculated to be ~10^{-6}J per switching cycle [6, 8]. It is worth mentioning here that realizing logic operation using frequency mixing technique is not specific to a certain device rather can be applied to resonators of any shape or size. Hence the performance parameters mentioned above can be improved by designing a suitable device with high integration densities, fast switching speed, and low energy consumption per cycle. With the advancements in areas of carbon nano tubes [14] and graphene based resonators [15], integration densities as high as ~10^8 with power ranging in 10^{-5}W and a switching speed of ~20Mz are quite viable.

(a)



(b)

In	C	OUT
0	0	Z
1	0	Z
0	1	0
1	1	1

(c)

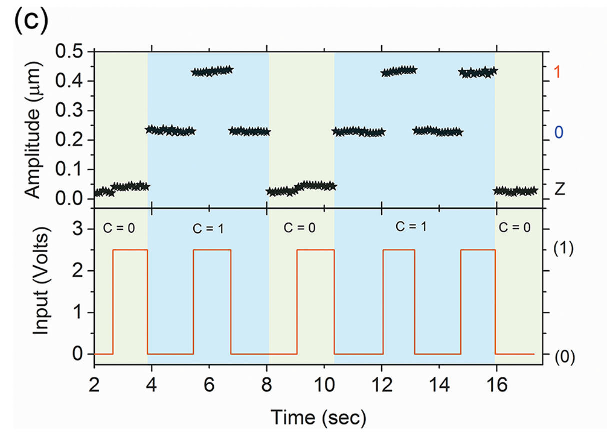


Figure 3: Demonstration of a tristate logic gate. (a) Microresonator electrical interconnects. (b) Truth table for tristate logic device. (c) The maximum response of the microbeam versus time for all the input logic states. “V_A” is the activation input voltage of 2.5 Volts constantly applied to the resonator at a frequency of 32 kHz. “C” is the typical control signal for the tristate logic operation applied at 94 kHz with an input value of 2.5 Volts. “In” is the input signal applied at 32 kHz.

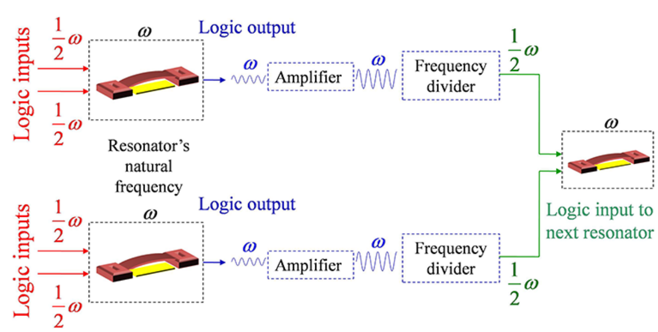


Figure 4: Proposed cascading scheme for AND/NAND gate. Resonators operating at half the resonance frequency respond at resonance frequency when combination resonance is activated. The output AC signal being weak is then amplified and finally divided into half to match the input signal. This input is then fed to the next AND/NAND gate.

Cascading resonant based logic devices in order to perform complex computing operations is rather a challenging task. Having similar signal waveforms for both input and output of the logic device provides a key step towards realizing this goal. However, the output signal received is weak and needs amplification to bring it to the input signal level. This can be achieved by adding an amplifier between two cascading gates. Another challenge specific to frequency mixing logic technique is that even though the resonator can be forced to resonate at any frequency via mixing, the output frequency with which the resonator vibrates is still the fundamental resonant frequency of the resonator. This issue can be addressed by adding a frequency divider after the amplification phase. A scheme for cascading these AND/NAND logic gates is illustrated in Figure 4. Driving the resonators with input signals at half the resonance frequency outputs a weak signal at the fundamental resonant frequency of the resonator. The signal is then amplified and its frequency is divided into half to match the input signal. This output signal can be then used as an input signal for the following device. In addition to the device capable of performing the tristate logic gate, the cascadability of the universal NAND gate allows for these gates to act as the basic building blocks to form complex logic operations to achieve MEMS based mechanical computing.

CONCLUSIONS

We presented a reprogrammable logic device capable of performing the fundamental logic operations of AND/NAND and a tristate logic gate using frequency mixing technique. AC inputs here are used as the gate inputs, which, in addition to unifying the input and output signal forms, provide an extra control parameter, i.e., the frequencies associated with these AC inputs. These frequencies are mixed to trigger the combination resonances, which are used here to an advantage to perform these logic functions. The use of frequency mixing allows us to execute these logic operations at any desired input frequency, which can be much higher or lower than the fundamental resonance frequency, provided the input conditions for activation of combination resonances are met. Furthermore, a scheme to cascade these logic devices is also detailed benefiting from the similar input and output signals resulting from using AC inputs for logic gates. This approach of realizing logic operations with a viable cascading scheme holds potential towards achieving MEMS/NEMS mechanical computers.

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