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A novel tuneable band-pass filter based on a single square-ring MEMS resonator

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Abstract

This paper reports a new MEMS resonator comprising of four identical beams connected at right angles in a square ring and utilizes the tuning of two neighbouring modes to construct a single resonator band-pass filter. A novel frequency tuning mechanism is introduced to accurately control the bandwidth and centre frequency. A representative measurement demonstrates continuous shift of the centre frequency and 3dB-bandwidth from 594.825 KHz to 595.180 KHz and from 1.02 KHz to 0.55 KHz, respectively, by varying DC bias voltages from -20 V to +20 V and the average ripple is 2.37 dB.

Keywords: Tunable filter; Resonator; MEMS

1. Introduction

Microfabricated silicon resonator based band-pass filters are being viewed as possible candidates to replace traditional crystal and SAW filters in signal processing applications with the added advantage of co-integration with CMOS electronics [1-3]. Most band-pass MEMS filter topologies usually couple several resonators in series with mechanical and/or electrical couplers to construct the desired band-pass filter response. However, fabrication and process tolerances represent a bottleneck for filter design and there are also limits to filter tunability.

This paper reports a silicon MEMS band-pass filter utilizing only one resonator. The filter demonstrates the possibility of tuning upper and lower stop-band frequencies and the filter bandwidth independently using separate tuning electrodes.

2. Design and fabrication

The tunable band-pass filter is fabricated using SOI MEMS technology. The optical micrograph of resonator is shown in Figure 1. The square-ring resonator consists of four beams orthogonally connected each other at the ends and anchors locate at the four corners to connect the resonator to the substrate. Four parallel plate electrostatic

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actuators (each consists of one beam and one fixed electrode) are used as four ports (as shown in Figure 1(A)) to drive the resonator in desired flexure modes and tune the filter.

Fig. 1. (A) Optical micrograph (15 µm beam width) and (B) simulated neighbouring mode shapes and natural frequency (ANSYS 11.0)

This resonator has two different modes with very close natural frequencies (simulated mode shapes and frequencies shown in Figure 1(B)), which will be coupled by using Port 1 (Figure 1(A)) as input and Port 2 as output. When the two peaks are sufficiently close, a band-pass filter characteristic is observed. The natural frequencies of the modes can be tuned independently by applying different DC bias voltages on Port 3 and Port 4 (tuning ports). It can be seen from Figure 1(B) that there is a primary vibration direction for each mode and the two modes are orthogonal to each other. The primary vibration direction of Mode A is horizontal and the direction of Mode B is vertical. When the DC bias voltage on the electrode located along the primary vibration direction of a given mode is changed, the natural frequency of this mode will be tuned while the natural frequency of other mode remains unchanged. For the device shown in Figure 1(A), increasing the DC bias voltage on Port 4 will decrease the natural frequency of Mode A independently and increasing the DC bias voltage on Port 3 will decrease the natural frequency of Mode B independently. Therefore, an electrostatic tuneable band-pass filter is implemented wherein the bandwidth and centre frequency can be controlled independently. The centre frequency and tuning range of this filter are defined by the dimensions of resonator and the maximum available DC bias voltage applied on the tuning ports.

This device was fabricated using SOIMUMPs process. The device layer silicon thickness is 25±1 µm, the length and width of each beam are 410 µm and 15 µm, the length of fixed electrode is 280 µm and the gap of parallel plate actuator is 2 µm. In order to study the scaling effects, a second resonant-filter device with the same dimensions but 10µm beam width was also co-fabricated in the same process.

3. Measurement and discussion

The resonant-filter is operated in vacuum with +20V DC bias applied on the beams and an input AC power of -10 dBm. Figure 2(A) and (B) shows the S_{21} parameters (magnitude in black line and phase in blue line) of the filter with beam widths of 15 µm and 10 µm, respectively, when port 4 and port 3 are grounded. The two sharp stop-band valleys in the magnitude response are due to the coupling of the feed through capacitor with phase inversion [1]. When port 3 is grounded and a tuneable DC bias is applied to port 4, the lower stop-band frequency will shift up with the positive DC bias and shift down with the negative DC bias (shown in Figure 3(A)). It can be seen that the lower stop-band frequency changed from 594.551 KHz to 594.798 KHz but the upper stop-band frequency only changed from 594.406 KHz to 594.433 KHz when the DC voltage on port 4 tuned from -15V to +15V. Similarly, when port 4 is grounded and a tuneable DC bias is applied to port 3, the upper stop-band frequency shifts in the same way (shown in Figure 3(B)). It can also be seen that the upper stop-band frequency changed from 595.305 KHz to 595.545 KHz but the lower stop-band frequency only changed from 594.747 KHz to 594.780 KHz when the DC voltage on port 3 tuned from -15V to +15V. Thus, it can be found from the above results that the tuning of the resonant frequency for the two modes can be achieved relatively independently. The maximum and minimum bandwidth is achieved by applying +20V on port 3/ -20V on port 4 and +20V on port4/ +20V on port 3 in our measurement. The results show that the maximum 3-dB bandwidth of the filter with a 15 µm wide beam is 1.020 KHz and the minimum bandwidth is 0.550 KHz (shown in Figure 4(A)). The maximum 3-dB bandwidth of filter with 10 µm wide beam is 0.782 KHz and the minimum bandwidth is 0.462 KHz (shown in Figure 4(B)) It can also be noticed from Figure 4 that the tuning range of lower stop-band does not equal to the upper stop-band and the resonant peak of lower stop-band is also not the same as the upper one. This is due to the fabrication tolerances associated with the gap sizes between the electrodes located along the horizontal and vertical directions and can be confirmed by SEM. A smaller gap size will result in a larger tuning range with lower DC voltage.

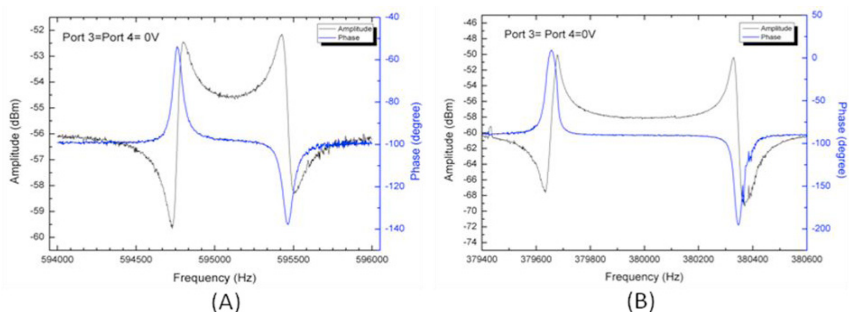

Fig. 2. S_{21} measurement results of two filters with (A)15 μm beam width and (B)10 μm beam width without applying tuning voltage

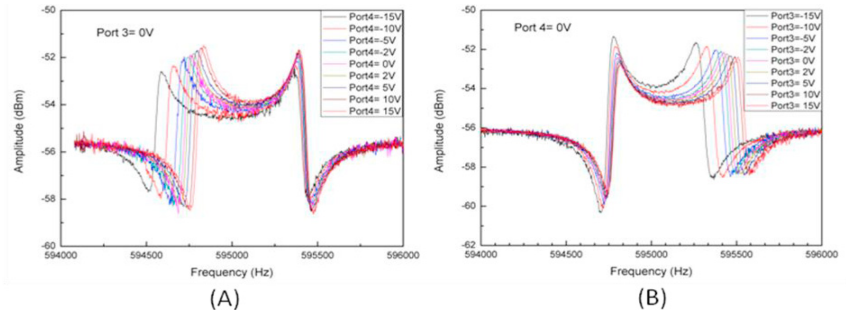

Fig. 3. (A) Tuning the lower stop-band independently (B) Tuning upper stop-band independently

When the tuneable DC bias is applied to port 3 and port 4 simultaneously, the centre frequency will shift without changing the 3dB-bandwith. As shown in Figure 5(A), the centre frequency shifts from 594.825 KHz to 595.180 KHz with the 3-dB-bandwidth 697±5 Hz when the DC voltage is changed from -20V to +20V. The relationship between DC bias on port 3 and 4 and frequency shift dependence of two resonant peaks is shown in Figure 5(B). The plot shows a linear relationship between the squared frequency and squared voltage modelled by the electrical spring softening effect. The measured 3-dB-bandwidth of the filter is about 10X larger than that obtained from FEM simulation (as shown in Fig. 1(B)), due to the fabrication tolerances associated with the horizontal and vertical beams. Thus, a narrower pass-bandwidth can be achieved by fabrication process enhancements.

In order to study the scaling effect of this resonant-filter, Table 1 compares the measurement results of the two devices with 10 μm and 15 μm beam width, respectively. It can be found from Table 1 that the ratio of centre frequencies of these two devices is about 1.56 which is nearly equivalent to the ratio of their widths. According to the Euler-Bernoulli theory, the resonant frequency of fundamental mode and higher modes of clamped-clamped beam (CC-beam) is given by:

$$\upsilon_1 = 1.027\sqrt{\frac{E}{\rho}}\frac{w}{L^2},\ \ \upsilon_n/\upsilon_1 = 2.756, 5.404 \text{ and } 8.933 \text{ for } n = 2,3,4 \qquad (1)$$

It can be seen that the resonant frequency of CC-beam resonator is proportional to the width of beam as observed. This result indicates that the resonant frequency of the square-ring resonator has a similar scaling characteristic to the CC-beam resonator.

4. Conclusion

A novel tuneable band-pass filter based on a single MEMS silicon square-ring resonator is reported in this paper. This filter utilizes two vibration modes of the square-ring resonator which have closely spaced resonant frequencies. Two devices with different beam widths were fabricated in the SOIMUMPs process and were measured to derive the performance of the filter and study scaling effects. The results indicate that the centre frequency, bandwidth, tuning range and tuning voltages are geometrically dependent on the dimension of the resonator and therefore this concept can be extended to higher frequency bands by uniformly scaling down the geometrical dimensions. The self-coupling mechanism of the square-ring resonator enhances the design flexibility for silicon based MEMS resonator filters.

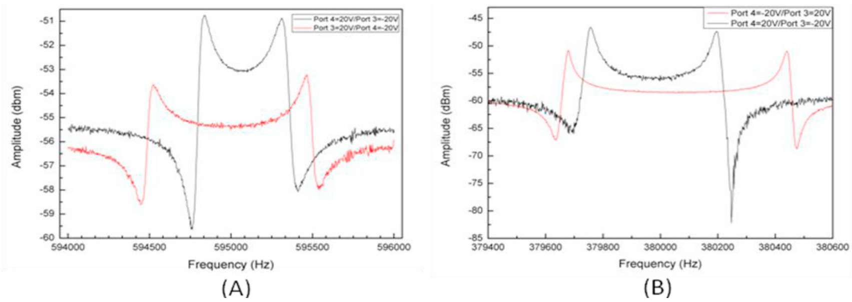

Fig. 4. (A) Min/Max bandwidth of filter with 15um beam (B) Min/Max bandwidth of filter with 10um beam

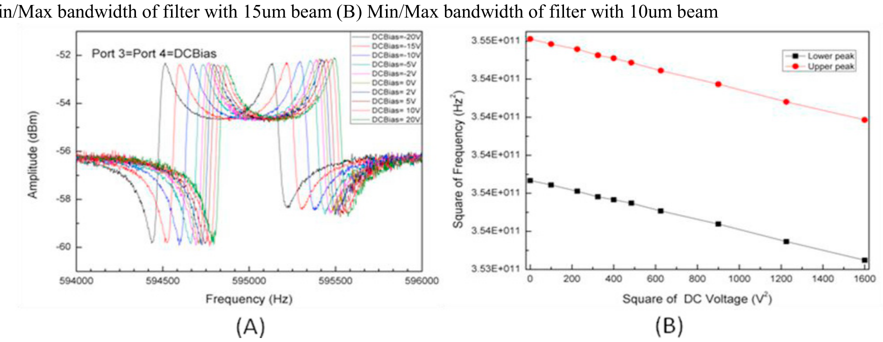

Fig. 5. (A) Tuning the center frequency without change bandwidth (B) Relationship between the stop-band frequencies and the tuning DC voltage

Table 1. Characteristic comparison of filters with 10 μm and 15 μm beam width

Beam width of resonator	**10 μm**	**15 μm**
Minimum 3-dB bandwidth	462 Hz	550 Hz
Maximum 3-dB bandwidth	782 Hz	1020 Hz
Minimum centre frequency	379.726 KHz	594.825 KHz
Maximum centre frequency	380.116 KHz	595.180 KHz
Constant 3-dB bandwidth	671 Hz	697 Hz
Ratio of bandwidth/centre frequency	1.216‰ (Min) 2.058‰ (Max)	0.924‰ (Min) 1.713‰ (Max)

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