Effect of Nonuniform Loading Layer on Monolithic Thickness-Mode Piezoelectric Filters

Wanling Pan, Reza Abdolvand*, and Farrokh Ayazi
School of ECE, Georgia Institute of Technology, Atlanta, GA, USA
(*Now with School of ECE, Oklahoma State University, Stillwater, OK, USA)

***Abstract* — The effect of using a nonuniform loading layer on the frequency response of a thickness-mode piezoelectric filter is investigated. The goal is to create multiple peak frequency shifts by one extra loading layer on the filter structure. By varying the area of the loading layer, not only the peak frequency is shifted but also extra bandpass filters are created at an offset from the original filter. This may enable the fabrication of compact filter arrays for multi-channel systems. Preliminary measurement results show up to 300MHz frequency shift for acoustically coupled piezoelectric-on-substrate filters operating at 1.2-1.5GHz.**

Keywords- frequency shift;multiple channels; loading; variable area

I. INTRODUCTION

In modern telecommunication systems, it is often desired to have filter arrays consisting of narrowband filters tightly spanned over a frequency range in order to maximize the number of communication channels allocated in a specific frequency band. To create predictable and considerable frequency offset in thickness mode acoustic filters such as film bulk acoustic resonator (FBAR) filters, the thickness of the resonant structure is usually altered. Ladder-type FBAR filters are networks of electrically coupled resonator filters. To achieve the desired passband width and out-of-band rejection, each filter usually consists of two groups of resonators connected in series or shunted to the ground, as shown in Fig. 1. Approximately, the series resonance frequency of the resonators in the series branch equals the parallel resonance frequency of the resonators in the shunt branch. Thus in an integrated process, the resonance frequencies of the shunt resonators has to be lowered compared to the series ones. This frequency shift is usually realized by the uniform deposition of an extra loading layer, such as SiO_2, on the shunt resonators [1]. In this approach, the frequency is determined by the thickness of the loading layer, thus each loading layer can create only one frequency offset. If *N* channels are to be implemented in the system, *2N* thicknesses are needed, implying at least *2N-1* loading layers and accompanied more complexity in fabrication.

In this work, we propose and study an alternative approach and create multiple frequencies by a single fabrication step. Thin-film piezoelectric-on-substrate filters [2] are chosen to reduce the total number of resonators in one filter. Frequency offsets are created by a loading layer whose area is variable for different filters. The frequency offset is correlated to the area of the loading layer. An array of filters with peak frequency variation of up to 20% have been created.

This work is supported by the DARPA Analog Spectral Processor project.

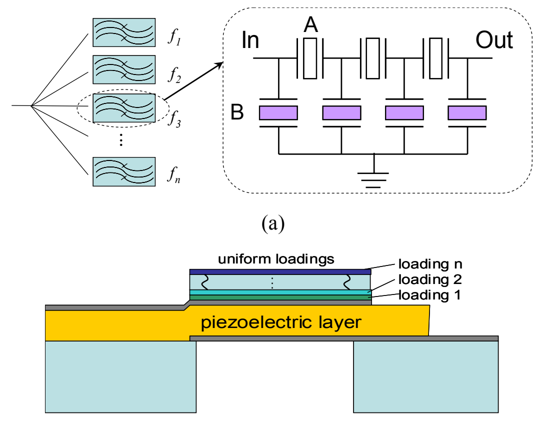


Figure 1. (a) System and filter architecture and (b) schematics of a single resonator for ladder-type FBAR filter based multi-channel systems.

II. SIMULATION AND DESIGN

A thickness-mode thin-film piezoelectric-on-substrate (TPoS) filter consists of two mechanically coupled regions defined by the electrodes, as shown in Fig. 2. The two regions can vibrate in-phase or 180° out-of-phase in the thickness direction, resulting in two peaks in the frequency response. Such a structure can be approximated by two coupled thickness-mode resonators. In a simple case, the two coupled resonant regions are identical and the operating frequency of

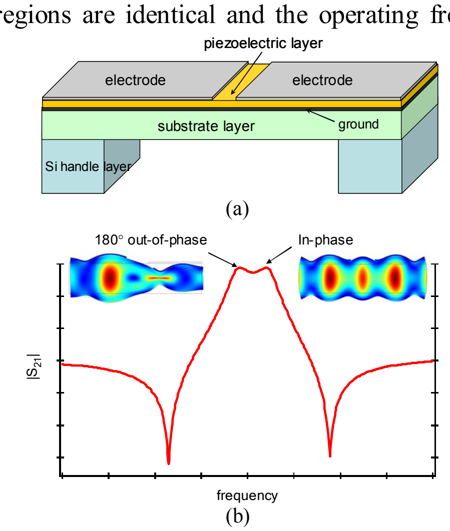
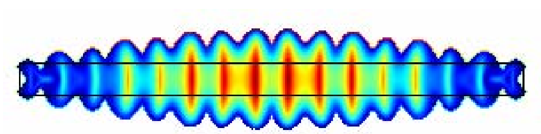


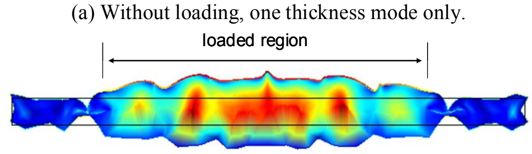
Figure 2. (a) The schematic view and (b) mode shape illustration and simulated frequency response of a thickness-mode TPoS filter.

the filter is in the vicinity of the resonance frequency of a single resonator with the structure of one of the regions.

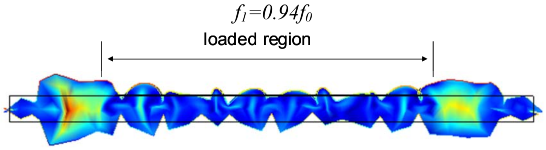
A single resonator's frequency will shift when loaded by an extra element. Two special cases have been widely studied. In one case, where the loading element is very small in area or mass, a small shift in the frequency can be detected and this behavior has been used in mass sensing applications [3]. In another case, loading is uniform on the surface of the resonator, and the shift can be calculated by Mason's model [4, 5]. However, situations in between these two cases, *i.e.*, when a resonator is nonuniformly loaded by a layer comparable to its area and mass, have not been extensively studied. To investigate that, finite element analysis has been carried out on a 2-D simple structure using COMSOL. The structure consists of a 100µm×5µm ZnO film with a 100nm-thick Au loading layer in the center of its surface. The loading layer's length varies from 0 (unloaded) to 100µm (fully loaded). The mode shapes of such a structure are simulated, as shown in Fig. 3. It is seen that when the structure is unloaded (Fig. 3(a)) or uniformly loaded (Fig. 3(c)), only one main thickness mode exists for the first order harmonic. When the structure is partially loaded, there exist two main thickness modes determined by the loaded area, such as the one shown in Fig. 3(b). Maximum surface displacement takes place in the loaded region in one mode and in the unloaded regions for the other mode, which has a higher frequency. By increasing the loaded area, not only the frequency of each mode changes, the lower frequency mode also becomes more prominent. For different loading layer's materials, one that has a higher mass density ρ results in a larger frequency shift. Simulation shows that when the ZnO layer is uniformly loaded with 100nm of Au (ρ=19300 kg/m^3), 6% frequency shift can be obtained, whereas when Cu (ρ=8700 kg/m^3) or Al (ρ=2700 kg/m^3) of the same thickness is used for loading, the frequency shift is as small as 2.5% and 0.7%, respectively.



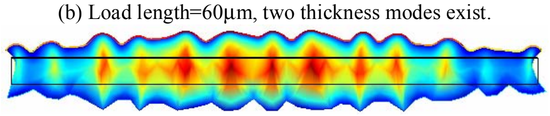
$f=f_0$
(a) Without loading, one thickness mode only.



$f_1=0.94f_0$



$f_2=0.98f_0$
(b) Load length=60µm, two thickness modes exist.



$f=0.94f_0$
(c) Uniformly loaded, one thickness mode only.

Figure 3. Simulated resonance mode shapes of a 100×5µm^2 ZnO film loaded by a thin Au layer of 100nm thickness and variable width.

Interdigitated structure is designed for the top electrodes. This structure enables the suppression of the spurious modes and provides flexibility in bandwidth control [6]. On each filter, multiple loading layers are added to the top electrode fingers, as shown in Fig. 4.

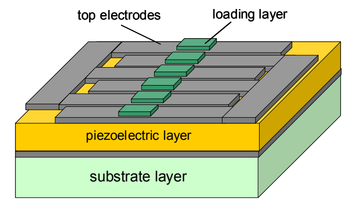
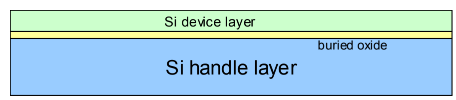


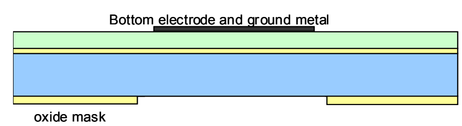
Figure 4. The schematic view of a TPoS filter with interdigitated top electrode and loading layers.

III. FABRICATION

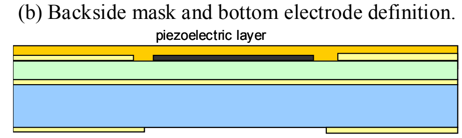
An array of filters are fabricated, with the abbreviated process flow shown in Fig. 5. The process is based on an SOI wafer with Si device layer of about 4µm thickness. Backside etching mask of SiO_2 is first patterned. The bottom electrode and the ground plane layer is deposited and patterned, followed by the deposition of about 1µm ZnO layer. The ZnO layer is then patterned to open contact to the ground plane. The interdigitated top electrode of 100nm Al is deposited and



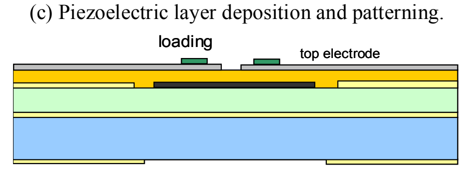
(a) SOI wafer preparation.



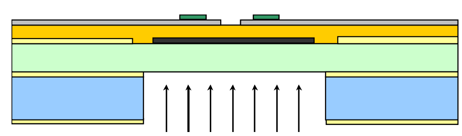
(b) Backside mask and bottom electrode definition.



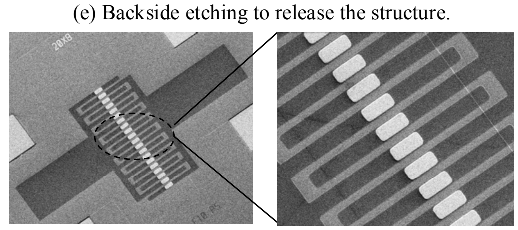
(c) Piezoelectric layer deposition and patterning.



(d) Top electrode and loading layer deposition and patterning.



(e) Backside etching to release the structure.



(f) The SEM image of a filter with loading layer.

Figure 5. The abbreviated process flow and the SEM image of a loaded filter.

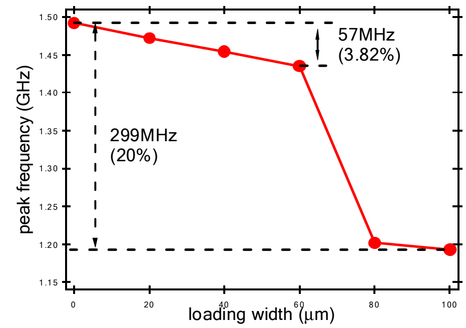
patterned, followed by the deposition and patterning of the Au loading layer of about 100nm thickness. Finally, the handle wafer and the buried oxide layer are etched from the backside to release the whole structure. The SEM image of such a filter is shown in Fig. 5(f), where the 20×8μm^2 rectangular loading layers are seen on the top electrodes. The temperature of the process does not exceed 300°C and is compatible with the standard CMOS process.

IV. MEASUREMENT

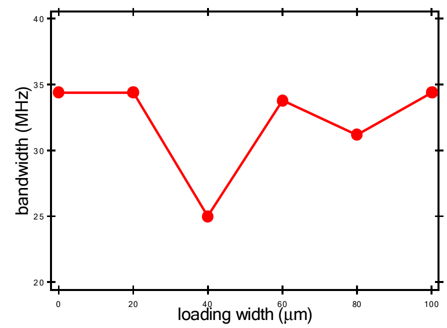
An array of filters, each having 10 pairs of top electrode fingers of 100×10μm^2 separated by 5μm, have been measured. The loaded area on each finger varies from 20×8 μm^2 to 100×8 μm^2. The $|S_{21}|$ frequency response plots of the second order resonance mode are shown in Fig. 6. It is seen that when the top electrodes are partially loaded, a resonance mode of lower frequency is detected, whose intensity is related to the loading layer's area. When the electrodes are unloaded or are with maximum loading, only one mode is observed. The more prominent mode shifts from the high-frequency one to the low-frequency one with the increase of loaded area. This behavior is in good agreement with the predictions from the simulation results presented in Section II.

The peak frequency shift is plotted in Fig. 7(a). It is seen that in the cases where the high-frequency mode is dominant, the peak frequency shifts 57MHz, from 1492 to 1435MHz, when the loading width varies from 0 to 60μm. If only the peak frequency is counted without discriminating the mode, the total frequency shift is as large as 299MHz, or 20% deviation from the unloaded case.

The 3dB bandwidth of the filters is also measured and plotted, as shown in Fig. 7(b). No significant change in the bandwidth is observed. However, the IL exhibits some variations, with largest IL when the loading is 60μm×8μm on each finger. In that case, neither of the two modes shows a high resonance peak in the frequency response.



(a)



(b)

Figure 7. (a) Peak frequency and (b) 3dB bandwidth *vs.* loading layer's width in the filter array.

V. ANALYSIS AND DISCUSSIONS

Equivalent circuit analysis is applied to the measurements. The equivalent circuit is shown in Fig. 8, which consists of two resonant branches (R_m, L_m, C_m) coupled by an inductor L_c [7]. In this circuit, R_m, L_m and C_m are the acoustic loss, acoustic mass and acoustic compliance transformed to the electrical domain by the piezoelectric coupling. R_m also includes electric loss in the signal transmission. The shunt capacitor C_p is mainly determined by the static capacitance of the electroded

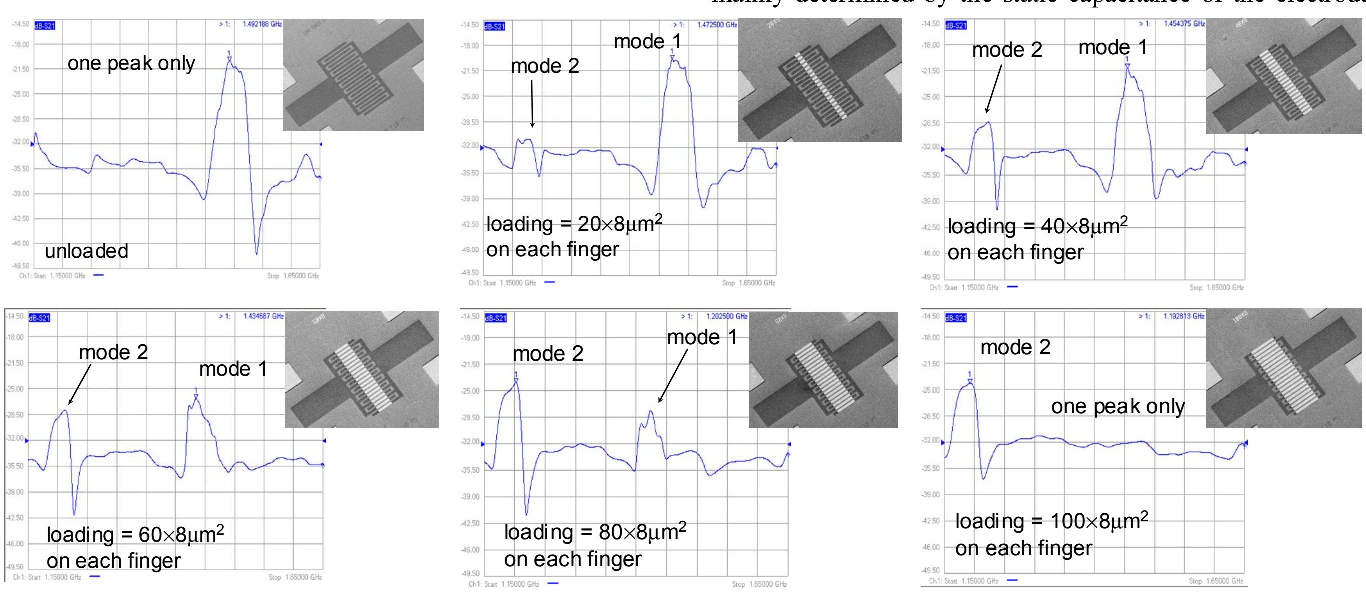


Figure 6. Measured frequency response of an array of filters with different loading width (50Ω termination).

regions and the shunt resistor R_p accounts for the loss due to the leakage and dielectric damping in the piezoelectric layer. A feedthrough capacitor C_f between the input and the output is also included.

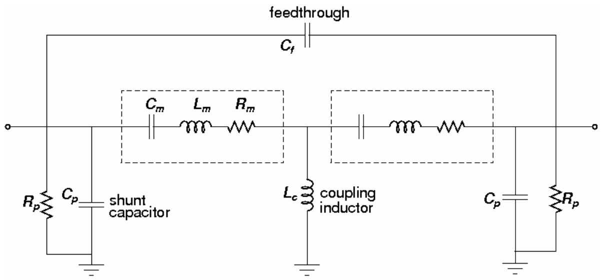


Figure 8. The equivalent circuit of a TPoS filter.

Such a circuit is fitted to the measurement results near the main resonance peak, such as the one shown in Fig. 9 for the unloaded case. Circuit elements in the unloaded, small loading (20×8μm^2 on each electrode finger) and maximum loading (100×8μm^2 on each finger) cases are compared, as listed in Table 1. It is seen that when the loading is small, only the series inductor L_m has to be changed to fit the new measurement compared to the unloaded case, implying that the main change in the structure is the acoustic mass. However, when the maximum loading is implemented, to obtain a good fitting, besides L_m, other elements including the series resistance R_m and the coupling inductor L_c also varies significantly from the unloaded case. The high IL largely comes from the large series resistance R_m, which may result from the small effective piezoelectric coupling factor and the large mechanical damping of the composite structure. R_m further increases when the loading layer's area becomes large. We attribute this increase to the larger mechanical damping factor of Au compared to ZnO and Si. Thus, when implementing such a frequency trimming mechanism, a material with low mechanical damping factor is preferred.

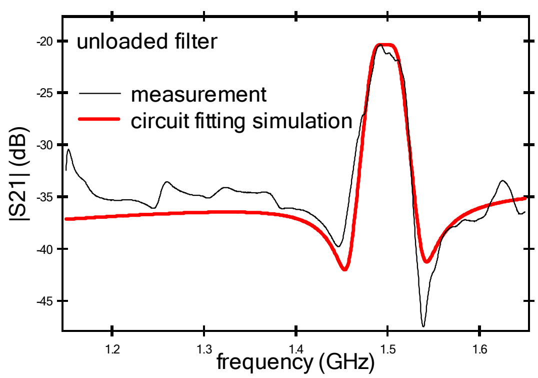


Figure 9. Equivalent circuit simulation fitted to the measurement data.

It is worth noting that although only the measurement results of the acoustically coupled filters are shown here. The method of creating multiple frequency offsets can also be applied to other types of acoustic wave resonators or filters such as single FBARs or ladder-type FBAR filters, as predicted by the simulation results presented in Section II.

Table 1. Element values in the equivalent circuit.

Item	without loading	small loading (20×8μm^2)	large loading (100×8μm^2)
R_m (Ω)	340	340	800
L_m (μH)	2.64	2.7	4.18
C_m (fF)	4.2	4.2	4.2
L_c (nH)	50	50	100
C_p (pF)	0.9	0.9	0.9
R_p (Ω)	250	250	350
C_f (fF)	30	30	50

VI. CONCLUSIONS

A method to create multiple frequency offsets in thickness-mode piezoelectric filters is proposed and investigated. This method utilizes a thin layer with variable areas loaded on the filter's electrodes. An acoustically coupled piezoelectric resonator filter array based on this method has been fabricated, in which the filters show frequency shift related to the loading layer's area. An extra bandpass filter is also created by the loading. Up to 20% frequency shift has been measured without significant change in the filter bandwidth. This method may enable the realization of multi-channel systems with simplified fabrication steps.

REFERENCES

[1] M.Ylilammi, J. Ellä, M. Partanen, and J. Kaitila, "Thin film bulk acoustic wave filter", IEEE Trans. UFFC. Vol.49, No. 4. 2002, pp. 535 – 539.

[2] R. Abdolvand and F. Ayazi, "Monolithic thin-film piezoelectric-on-substrate filters", IEEE/MTT-S International Microwave Symposium Tech. Digest, 2007, pp. 509 – 512.

[3] H. Campanella *et al.*, "Localized and distributed mass detectors with high sensitivity based on thin-film bulk acoustic resonators", Applied Physics Letters, Vol. 89, 033507, 2006.

[4] W. P. Mason, "A dynamic measurement of the elastic, electric and piezoelectric constants of rochelle salt", *Physical Review*, Vol. 55, pp. 775 – 789, 1939.

[5] J. F. Rosenbaum, *Bulk Acoustic Wave Theory and Devices*, Artech House, Inc., Norwood, MA, 1988.

[6] W. Pan, R. Abdolvand, and F. Ayazi, "A low-loss 1.8GHz monolithic thin-film piezoelectric-on-substrate filter", Proc. IEEE MEMS 2008 Conference, in press.

[7] L. N. Dworsky, "A comparison of band pass filter technologies for communications system applications", Proc. IEEE Ultrasonics Symposium, 1991, pp. 241 – 250.