ETCH-A-SKETCH FILTER

R. Wang and S. A. Bhave
Cornell University, Ithaca, NY, USA

ABSTRACT

This paper demonstrates an "Etch-A-Sketch" filter on a Z-cut lithium niobate (LN) thin-film. The filter consists of two resonators coupled by a reconfigurable phononic crystal that can be programmed by AFM-based post-release piezoelectric domain engineering. Specifically, we demonstrated a band-pass filter at 553MHz with 8.6MHz 3dB bandwidth (BW). Then, we "Etch-A-Sketch" periodically domain inverted patterns on the coupling element which changes the coupling impedance, and reduces the filter BW by 4.6%. This method only requires 80V (magnitude) to achieve domain inversion which is 100x lower than that required for bulk LN, and no DC bias voltage is required during RF operation.

KEYWORDS

lithium niobate, AFM-based piezoelectric domain engineering, phononic crystal, reconfigurable mechanical filter.

INTRODUCTION

There is a huge demand for mobile wireless communication systems that can re-utilize a common set of RF front-end components across disparate applications through programmable hardware architecture. Such systems require RF filters that can be tuned to fit the particular application. Filters based on SAW, FBAR, contour-mode AlN and air-gap resonators are the prevailing technologies for mobile wireless communication devices because of their small size, high quality factor, wide bandwidth and low insertion loss. However, they are pre-configured and it is difficult to modify their frequencies and bandwidths (BW) once they are manufactured. Previous work [1] has shown a new type of MEMS resonator based on lithium niobate thin film. Through piezoelectric domain engineering, the electromechanical coupling coefficients of different harmonic mechanical modes can be tailored and maximized. Therefore, the resonant frequency of such device can be programmed post-manufacture by choosing which mechanical mode to excite. In-field synthesis of diverse filter response not only requires frequency-agile resonators, but also reconfigurable mechanical coupling elements.

Traditionally, different frequency responses have been synthesized from mechanical-beams-coupled multiple resonators by using beams with different dimensions. These parameters cannot be drastically reconfigured after being manufactured. In this work, we present a novel re-programmable mechanical coupling element through tip-based piezoelectric domain engineering in lithium niobate (LN) thin-film. With the reprogrammable coupling element, we demonstrate a frequency response programmable "Etch-A-Sketch" band-pass filter.

DEVICE CONCEPT

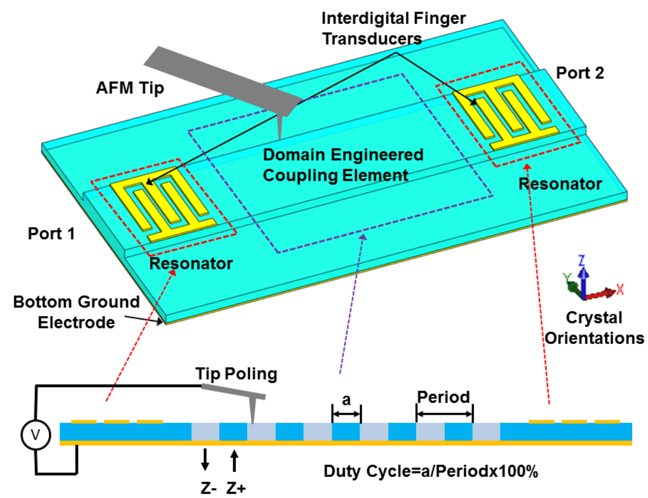

Figure 1: Conceptual schematic of the Etch-A-Sketch Filter.

Fig. 1 shows the conceptual schematic of the Etch-A-Sketch filter, which is designed for operation in A_0 Lamb wave mode on Z-cut LN thin-film. The reason for choosing Z-cut LN is that piezoelectric domain inversion of LN on Z-cut LN can be conveniently performed with commercially available single tip AFM systems. The filter consists of two resonators excited by interdigital transducers (IDTs) with bottom ground electrode, and the resonators are interconnected by a piezoelectric domain engineered coupling element. The resonators are unconventional in the sense that the acoustic confinement is achieved through the grating effect of the IDTs, rather than through anisotropically etched boundaries. The acoustic wave is excited to travel in the crystal x-axis to exploit the strong d_{15} coefficient of LN. This also minimizes the excitation of spurious modes from different mode families as the relevant *d* coefficients for spurious mode families are either zero or much smaller than d_{15}. The device resembles a mechanical beam coupled dual-resonator filter. However, the key difference is that the coupling beam is replaced by a slab acoustic waveguide, where the piezoelectric domain of the material is periodically inverted. The behavior of Lamb waves in piezoelectric thin-films is strongly affected by the electrical boundary condition. As domain inversion in conjunction with the uniform bottom ground electrode equivalently changes the electrical boundary conditions, periodically inverted domains causes periodical perturbation of the boundary condition creating an acoustic grating (a.k.a. 1-D phononic crystal). The frequency response of the grating can be easily programmed by changing the period, duty cycle and number of periods of the domain patterns through AFM tip domain inversion. As a result, different frequency responses can be synthesized in-field by programming the phononic crystal. It should be noted that the ground electrode also provides electrical contact during domain inversion.

Table 1: Design parameters of the simulated device.

Parameters	**Value**
Slab waveguide width	55um
Slab waveguide length	85um
Periods of domain inverted grating	18
Period of domain inversion	4um
Duty cycle of the grating	50% (2um)
Period of IDT fingers	3um
Number of IDT fingers	13
IDT finger width	1.5um

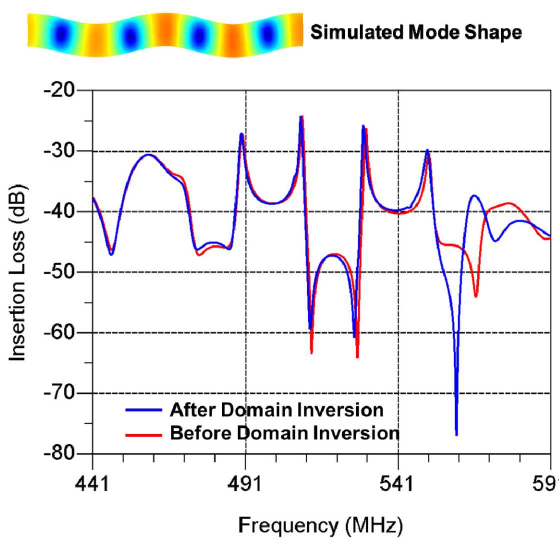

Figure 2: FEA simulated mechanical mode deformation of a short section of the device, and simulated insertion loss of the Etch-A-Sketch filter before and after piezoelectric domain engineering.

Fig. 2 shows the simulated mode shape of a short section of the device and insertion loss of the Etch-A-Sketch filter before and after domain inversion. The design parameters of the simulated device are listed in Table 1. As expected, the device operates in A_0 mode. Since power reflection coefficient of the IDTs has a shape of $\tanh^2$, the resonators support several harmonic A_0 modes within the reflection window. After introduction of domain inversion in the FEA simulation, the resonances shifted left to lower frequencies resulting in a 2~6% 3dB bandwidth tuning. Intuitively, this is because the frequencies of the A_0 modes are off resonance of the domain engineered grating and the periodical E-field shorting effect from electrode-shorted periodic domains "softens" the material which reduces the acoustic velocity of the coupling element.

FABRICATION

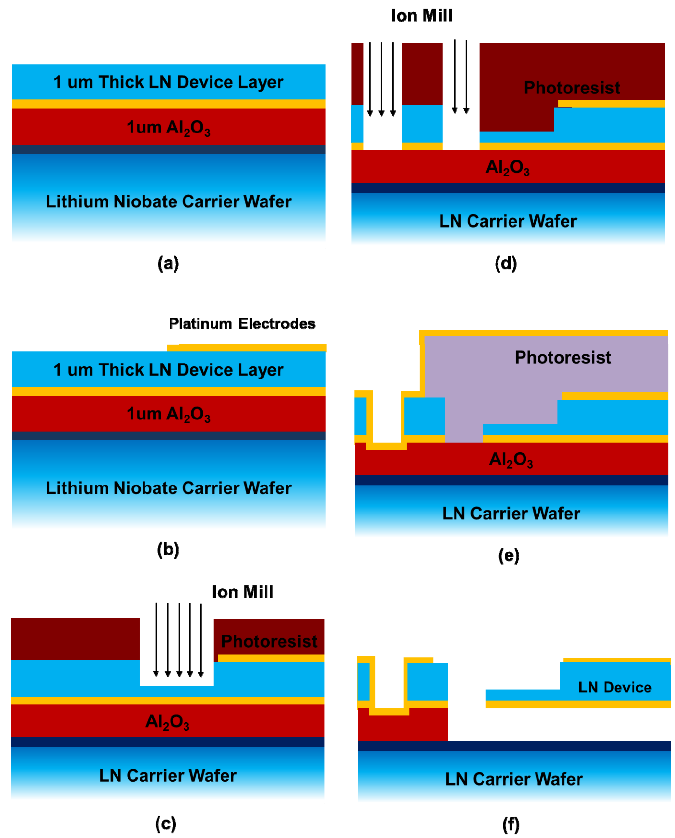

Figure 3: Fabrication process of the Etch-A-Sketch Filter: (a) the fabrication begins with a z-cut LN thin-film wafer with 1um thin LN device layer, 0.1um Cr bottom electrode, and 1um thick alumina sacrificial layer; (b) 100nm Pt top electrode is defined by lift-off; (c) a timed shallow ion-mill etching is used to define the slab profile; (d) a deep ion-mill etch is used to etch into the alumina exposing the Cr layer and defining the device geometry; (e) a 200nm conformal gold layer is deposited to refill the ground vias; (f) devices are released in TMAH at 92°C then dried in critical point dryer.

Similar to [2], the fabrication (Fig.3a~f) of the Etch-A-Sketch filter begins with a white Z-cut LN wafer deposited with a 100nm thick Cr film for the bottom electrode and a 1um thick alumina sacrificial layer. The device wafer is then flip-bonded to a Z-cut LN carrier wafer and polished down to 1um thin. After defining the platinum IDTs (10nm Cr/ 100nm Pt) by lift-off, the slab profile is defined using a timed ion-mill etching with photoresist mask, which etches into the thin film by ~600nm. Next, another deep ion mill etching is used to define the device geometry and exposes the bottom Cr electrode. As there is no etch stop layer for the ground via, the Cr metal layer is etched through and a 200nm thick conformal gold layer defined by lift-off is used to refill the etched vias and achieve ground contact. Finally, the devices are released in 4.9% tetramethylammonium hydroxide (TMAH) at 92°C heated with water bath followed by critical point drying (CPD). Figs. 4a and b show the SEM and the microscopic photo of a fully released device. The small signal probe pad is designed to minimize the pad capacitance. The slab appears green in the microscopic photo as it has different thickness than the mesa. It is worth to note that the residue stress in the released device is significant because of the LN/Cr bimorph structure. The ground vias and the corners of the etched device geometry are rounded to prevent the device from cracking through the sharp etched corners.

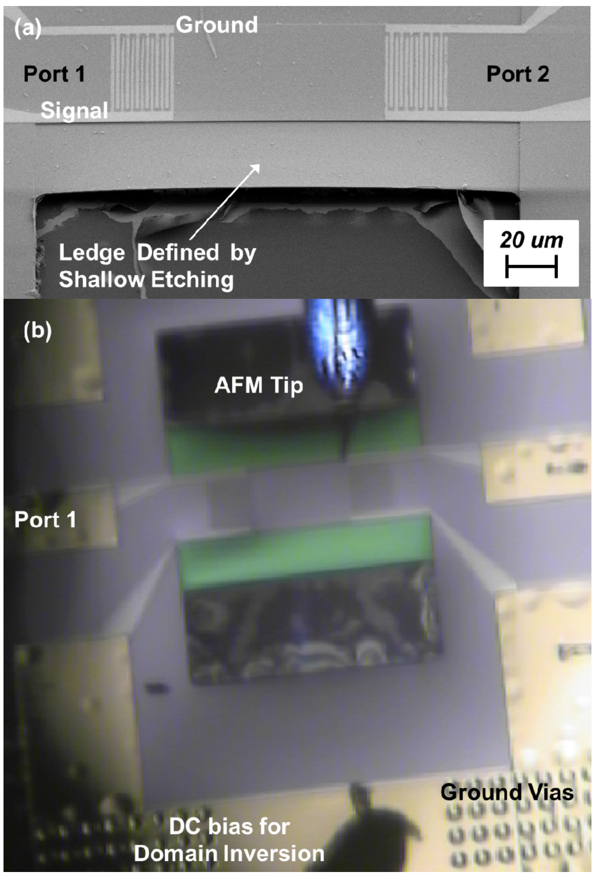

Figure 4: (a) SEM of a fully released Etch-A-Sketch filter with the same design parameters in Table 1; (b) Microscopic photo of the same device.

Experiments

Device Reconfiguration

An Asylum MFP-3D AFM system was used to perform the domain patterning of a device that has the same design parameters in Table 1. The membrane was scanned continuously (25um/s) in contact mode while applying periodic voltage to the AFM tip to invert the domain direction of the membrane (Fig. 5). A low spring constant (0.3N/m) solid platinum AFM tip (Model No.: 12Pt400B, Rocky Mountain Nanotech.) was used to minimize the stress on the membrane during domain writing and providing good electrical contact. While the slab structure provides acoustic confinement in the transverse direction, it also prevents the tip from dropping-off the membrane causing damage to the AFM tip and the device. The bottom electrode is grounded using a DC probe to improve the fidelity of domain patterning (Fig. 4b). As the LN film is only 1um thick, the required voltage to surpass the coerce field of LN [3] is reduced by over 100× as compared to bulk LN. In this work, 80V (magnitude) was sufficient to ensure high contrast domain inversion. The inverted domain pattern was verified by piezoresponse force microscopy (PFM). Fig. 5 shows the surface roughness of the membrane and the phase of the piezo-response. The AFM scan does not cause discernable damage to the membrane surface, and the domain inverted acoustic grating has a period of 4μm in the crystal x-direction. The violet color indicates the thin film moves out of phase with the PFM excitation, and yellow indicates in phase motion (opposite polarity). After domain inversion, both the y-axis and z-axis of the domain are inverted, while the orientation of the x-axis remains unchanged [4].

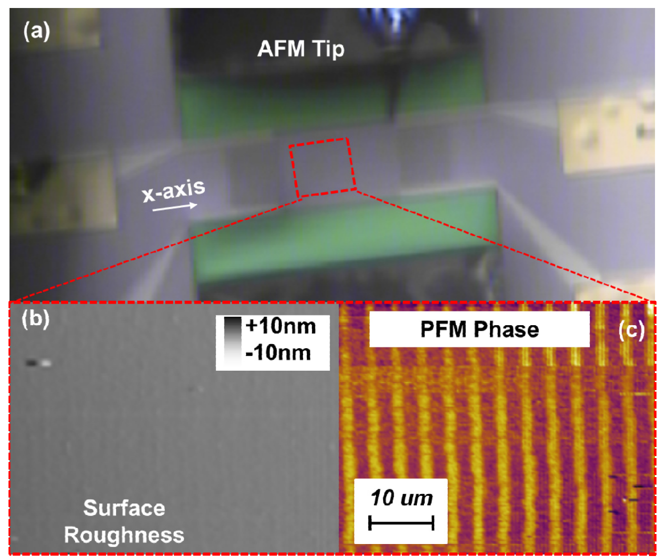

Figure 5: Periodic domain inversion along the crystal x-axis on Z-cut LN thin film using AFM tip: (a) Microscopic photo of the device during domain inversion; (b) Surface roughness of the coupling element after domain inversion showing no discernable surface damage; (c) Phase of the piezoresponse force microscopy showing the periodically inverted domains.

Measurements

Standard 2-port measurements using an Agilent E8364B PNA were performed on the device before and after domain engineering. No de-embedding was performed.

Fig. 6 shows the broadband insertion loss of the Etch-A-Sketch filter before and after domain patterning from 0.2GHz to 1GHz. The sinc function shaped ripples centered at 286MHz reflects the transduction efficiency for the lowest order A_0 modes that can be excited by the IDT design. As this frequency is half of the center frequency of the first reflection window of the IDT, the resonators do not support resonances around 286MHz, and the device behaves like a Lamb wave delay line. On the other hand, it can support harmonic A_0 modes centered at 572MHz. Because of the finite reflection window of the IDT, the harmonic A_0 modes cause spurious response close to the targeted band-pass response. No de-embedding and impedance matching were attempted; therefore the in-band ripple is not optimized.

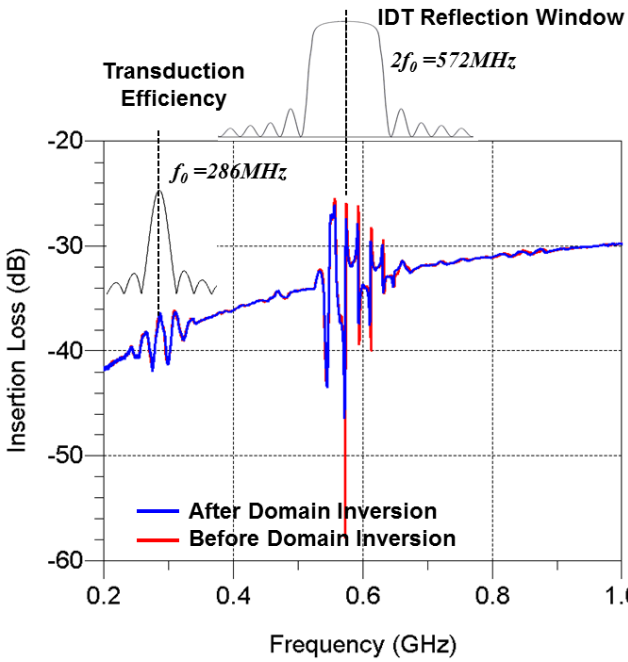

Figure 6: Measured broadband insertion loss of the Etch-A-Sketch filter before and after domain patterning.

Fig 7 shows the zoom-in view of the measured band-pass responses with a center frequency of 553MHz. The absolute 3dB bandwidth of the first pass band is 8.6MHz before poling, resulting in a 1.6% relative BW. After domain inversion, the BW is reduced by 4.7%. The experimental result follows closely to the simulated insertion loss with or without domain engineering, except that the absolute center frequency is shifted by ~14% which is due to manufacture uncertainties, inaccuracy in the material models.

CONCLUSION

We demonstrated an Etch-A-Sketch filter, in which two resonators are coupled by piezoelectric domain engineered phononic crystal. The coupling impedance can be programmed by "writing" periodic domains on the membrane with different periods, numbers of periods and duty cycles. Our initial investigation demonstrates 8.6MHz 3dB BW band pass filter at 553MHz. The BW is tuned by 4.6% with domain engineering. More importantly, this technology is frequency agnostic. In conjunction with frequency agile MEMS resonators (such as [1]), this technology will enable in-field synthesizes of diverse filtering responses for reconfigurable RF MEMS front-ends.

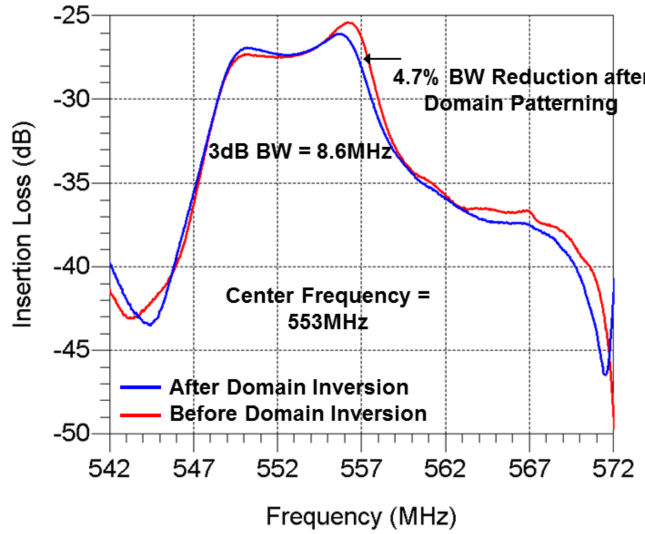

Figure 7: Zoom-in view of the measured insertion loss of the Etch-A-Sketch filter before and after domain engineering.

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CONTACT

*R. Wang; rw364@cornell.edu