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5GHz Band n79 wideband microacoustic filter using thin Lithium Niobate membrane

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Microacoustic resonators made on suspended continuous membranes of LiNbO3 were recently shown to have very strong coupling and low losses at 5 GHz and above, suitable for high performance filter design [1]. Employing these simple resonator structures, we have designed, fabricated, and measured a 4.7 GHz bandpass ladder-type filter having 1 dB mid-band loss and 600 MHz bandwidth to address the 5G Band n79 requirements. The filter is fabricated on a monolithic substrate using standard i-line optical lithography and standard semiconductor processing methods for membrane release, starting with commercially-available ion-sliced wafers having 400 nm thickness crystalline LiNbO3 layers. The filter is well-matched to a 50 Ohm network and does not require external matching elements. Through accurate resonator engineering using our finite element method software filter design environment, the passband is spurious-free, and the filter provides better-than 30 dB rejection to the adjacent WiFi frequencies. This filter demonstrates the performance and scalable technology required for high-volume manufacturing of microacoustic filters above 3.5 GHz.

Introduction: Mobile handsets rely on miniaturized high-performance RF filters to implement their increasingly complex architectures, with a recent drive from new 5G standards to high frequencies well above 3 GHz and wide bandwidths above 10%. This presents strong challenges for incumbent LiTaO3/LiNbO3-based surface acoustic wave (SAW) and AlN-based bulk acoustic wave (BAW) technologies which are generally limited by lower acoustic coupling, around 3% bandwidth, and the increasingly smaller dimensional requirements for high frequencies [2]. LTCC filters can support wide bands but require larger form factors, have higher loss, and lack the steep rejection enabled by high-Q acoustic resonators [3].

To address this need, we have recently demonstrated laterally-excited shear mode bulk acoustic wave resonators (XBARs) that have low losses and an extremely wide relative bandwidth of 11% at 4.8 GHz [1]. XBARs are formed with a relatively simple structure involving a metalized interdigitated electrode (IDE) system, but with small metallization ratio. The electrodes create predominantly horizontal electric fields which generate the half-wavelength bulk shear wave A1 resonance in the thin suspended $LiNbO_3$ membrane. The maximum acoustic amplitude is located in the free membrane area, between said electrodes. Due to the fundamentally different acoustic mode of the XBAR, the design trade-offs are very different from conventional microacoustic resonators. In SAW, the metallic IDT electrode pitch is intimately tied to the resonator frequency, and in both SAW and BAW devices the metal thickness strongly impacts the resonator frequency and quality factor. To produce a SAW resonator operating at 5.2 GHz comparable to our XBAR resonator, linewidths close to 2 μm would be required. For XBAR resonators, the frequency is determined primarily by the piezoelectric plate thickness. The IDE metal thickness, as well as width, is a secondary consideration as are the line spacings which span 3-5 μm and are easily produced with optical lithography. To realize the spurious free low-loss design of a monolithic bandpass ladder filter, a coating of SiO2 material on the shunt resonators is used to tune the operating frequency.

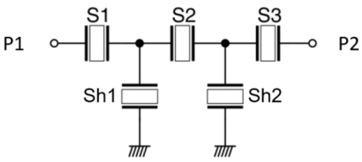

Fig. 1 *Schematic diagram of five-resonator, two-port prototype ladder filter using three series resonators and two shunt (parallel branch) resonators.*

Filter Design: Highly-accurate finite element method (FEM) simulations using Resonant's ISN© for both the microacoustic resonators [4,5] and electromagnetic circuit allow rapid design cycles exploring a large parameter space. The design procedure begins with synthesis of a lumped-element model for the resonators in the absence of any electromagnetic interconnect circuit simulation, as in Fig. 1, with the number of ladder sections determining the ultimate filter rejection level. Butterworth van Dyke (BVD) resonator parameters for the initial approximate prototype design are provided in Table 1, demonstrating the useful element values appropriate for RF filter design that can be achieved with this technology. These parameters were used for the initial BVD design of the filter shown in Fig. 2. At the following design steps, the filter is realized and optimized with FEM models for the XBARs and electromagnetic (EM) interconnects.

Table 1: Equivalent BVD circuit parameters for the resonators used in the prototype filter design.

Resonator	C0 [pF]	Cm [pF]	Lm [nH]	Fr [MHz]
Series 1	0.43	0.113	9.9	4746
Series 2	0.25	0.670	16.8	4717
Series 3	0.61	0.171	6.7	4696
Shunt 1	1.22	0.303	4.8	4165
Shunt 2	1.19	0.298	4.9	4147

Realizing the design with XBARs requires controlling and minimizing spurious modes which must be avoided in the critical regions of the filter. Special attention must be paid to the higher frequency A1-3 ("horizontal 3rd harmonic" resonance [1]), which has the same nature as the primary λ/2 thickness resonance A1 and is easily excited. Sharp parasitic propagating modes, such as the lowest order A0 and S0 Lamb modes and shear SH0 modes, can also be a problem. Although the resonators have moderate Q-factors -- estimated to be around 500 -- in combination with extremely high coupling we predict record-low minimal insertion loss of 1 dB near 5 GHz.

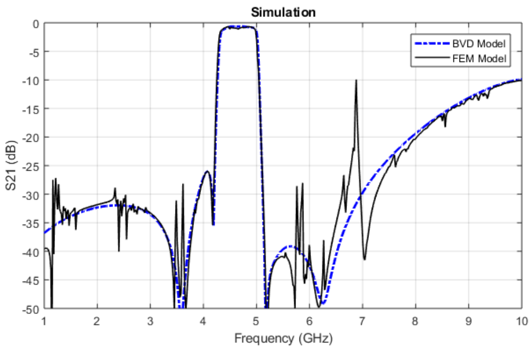

Fig. 2 *Simulation of the prototype XBAR filter near the 5G Band n79 frequency. Accurate FEM models for the resonators and EM interconnect layout allow filter optimization after the BVD model is realized.*

Fabrication: The XBAR filter is implemented on an ion-sliced 400 nm thin film of *ZY*-oriented single-crystal LiNbO3 bonded to a 250 μm thick Si carrier wafer from NanoLN [6]. Figure 3 shows a microscope image of the resulting filter. Frontside IDE lithography uses an ASML 5500 DUV stepper and liftoff process for the Al metal layer. A second pad metallization using thick Au reduces interconnect loss. A sputtered SiO2 coating layer is deposited on the shunt resonators, defined by lithography and liftoff. Subsequent XBAR membrane release is performed with a backside Si deep reactive-ion etch (DRIE) process, followed by a HF etch to remove the buried SiO2 bonding layer under the membrane. A frontside etch process is also possible, with Si DRIE performed through openings in the $LiNbO_3$ layer on the periphery of the IDE. In both cases, the released membranes are delicate and require special wafer handling. However, the membrane is solidly attached to the Si wafer on all sides and is more robust than the standard MEMS anchor attachment for suspended membranes. Following fabrication, the wafer is diced to release the filter chips.

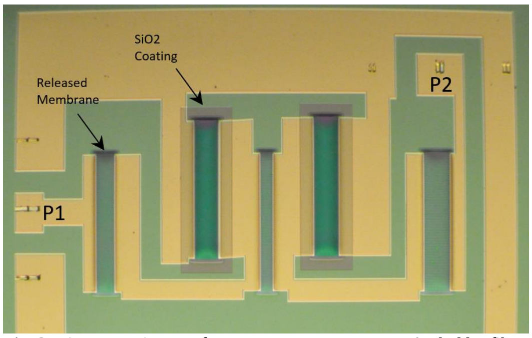

Fig. 3 *Microscope image of a prototype 5-resonator XBAR ladder filter. Etch-released membranes are visible as dark areas under each resonator and SiO2 overcoat is visible as a grey coating on the shunt resonators. IDE metallization is Al and interconnect metal has a second Au layer to reduce ohmic loss.*

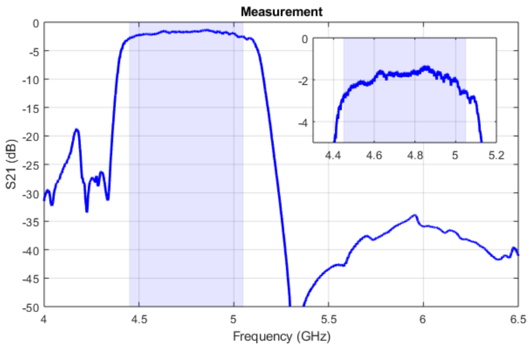

Fig. 4 *Wafer probe measurements of an improved XBAR filter showing 1.35 dB minimum passband insertion loss with a spurious-free 600 MHz bandwidth (shaded region) close to the 5G Band n79 specification. The singulated filter die size is 1.8 x 1.4 mm^2 and the part requires no matching elements to 50 Ohms. This filter is capable of 31 dBm input RF CW power handling at room temperature.*

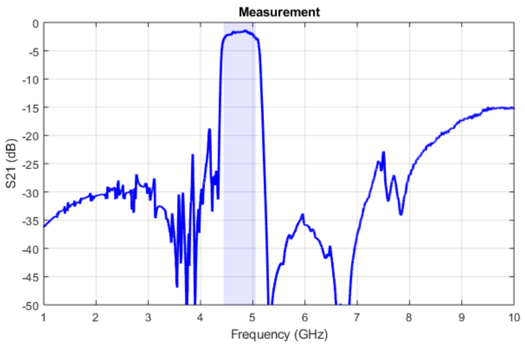

Fig. 5 *Wideband wafer-probe measurements of an improved XBAR filter showing good rejection and well-behaved response from 1-10 GHz.*

Results: Figures 4-5 present wafer-probe measured filter performance for an improved design showing over 600 MHz of bandwidth, 1.35 dB minimum insertion loss, adjacent WiFi rejection approaching 35 dB, and well-behaved wideband rejection all the way to 10 GHz. The measured passband shows the absence of strong spurious modes; however, small amplitude 12 MHz passband ripples are observed caused by backside acoustic reflections from the polished Si substrate. Some similar designs, specifically engineered to increase their RF power handling ability, have been measured to exceed 31 dBm CW input power at room temperature across the 600 MHz band. Further power handling improvement will continue.

Conclusions: We report the first measured results on a prototype ladder filter composed of laterally excited shear mode acoustic resonators (XBARs) fabricated from sub- mm thickness LiNbO3 platelets operating in the 5 GHz frequency range, suitable for 5G mobile phone applications. This filter demonstrates excellent performance and confirms that a new technology using ion-sliced mono-crystalline layers of $LiNbO_3$ opens new horizons in microacoustic filters. Although the acoustic wavelength in the XBARs is sub-micron, the electrode lithography does not need to scale well below this to produce lines on the order of λ/4, the technologically-challenging requirement that limits manufacturable SAW resonator frequencies. Furthermore, the strongly-coupled shear-mode resonance used in XBARs is largely decoupled from the IDE metal, resulting in excellent performance with considerable flexibility in engineering device performance. This Band n79 filter demonstrates the performance and scalable technology required for high-volume manufacturing of microacoustic filters well above 5 GHz.

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One or more of the Figures in this Letter are available in colour online.

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