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Fundamental mode 5 GHz surface-acoustic-wave filters using optical lithography

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Resonators and bandpass filters have been implemented in the 5 GHz frequency range, based on ''longitudinal leaky'' surface-acoustic waves on standard YZ-cut lithium niobate substrate. The synchronous one-port resonators constituting a ladder filter operate in the fundamental mode. The electrode width in the resonators is above 0.25 μm, thus making them readily accessible for fabrication with optical lithography. Test resonators are fabricated to study the effects of the metallization ratio and aperture on the resonator behavior. For the prototype filter, a center frequency of 5.20 GHz, a wide fractional 3 dB bandwidth of 6.3%, a minimum insertion loss of 3.3 dB and a high stopband suppression of 25 dB have been achieved. © *2003 American Institute of Physics.*
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In a recent paper[1] a surface-acoustic-wave (SAW) filter utilizing the ''longitudinal leaky'' (LL) wave was reported for the ''bluetooth'' frequencies, with the prototype filter center frequency being 2.5 GHz. It was also proposed that the high velocity of the LL wave ($\approx$6100 m/s) would render the 5 GHz frequency regime accessible using optical lithography. In this letter, we report experimental results for a SAW bandpass filter operating at wireless local area network (WLAN) frequencies above 5 GHz. The prototype filter is fabricated using standard optical lithography and its center frequency is as high as 5.2 GHz. The filter employs the fundamental LLSAW mode; no higher-harmonic operation needs to be exploited.

The recently emerged WLANs, such as the European HiperLAN standard, operate in the 5 GHz frequency regime. High operating frequency and wide bandwidth enable fast wireless data connections in office environments. The anticipated increase in the demand for bandpass filters at high-frequency bands has fueled attempts to extend the SAW operating frequency into the 5 GHz regime. The physical concept of operating SAW filters has already been proven at such high frequencies,[2] but the technology commonly used to fabricate the high-frequency prototypes has been electron-beam lithography (rather than optical lithography), which is inapt for mass fabrication.

An alternative approach for implementing high-frequency filters that has lately been under rapid development is the thin-film bulk-acoustic-wave resonator (FBAR) technology.[3,4] The challenge in the fabrication of FBARs is not the limited resolution of optical lithography, but rather the quality and uniformity of the thin piezoelectric film. The operating frequency is determined by the film thickness, which therefore needs to be controlled precisely. In the fabrication of SAW devices, only one or two mask levels (and equally many depositions of metal layers) are needed, which is substantially less than that needed for the fabrication of FBARs. Hence, if optical lithography can be used, the SAW fabrication process is simpler and more cost effective. Extension of SAW technology into the 5 GHz frequency regime (with optical lithography) makes the competition between these two approaches even more intense.

Our prototype filter, with its center frequency 5.2 GHz, is constructed using synchronous one-port SAW resonators operating in the fundamental mode. The SAW mode utilized is the so-called LLSAW, whose velocity is below that of the longitudinal bulk-acoustic wave (BAW), but quite close to it. The resonator and filter structures have been fabricated on a YZ-cut lithium niobate ($LiNbO_3$) substrate using conventional optical lithography. On YZ-$LiNbO_3$, the velocity of the LLSAW exceeds 6100 m/s. At 5.2 GHz, this results in approximately a 0.6 μm periodicity for the finger electrodes in the resonators. This implies critical dimensions of 0.25 μm or larger, which can be achieved using the standard optical lithography process employed in SAW fabrication today. Hence, mass fabrication of SAW filters for the 5 GHz regime appears quite feasible. Furthermore, the electromechanical coupling constant is strong and, hence, LLSAW on YZ-$LiNbO_3$ may be used as a SAW propagation mode for

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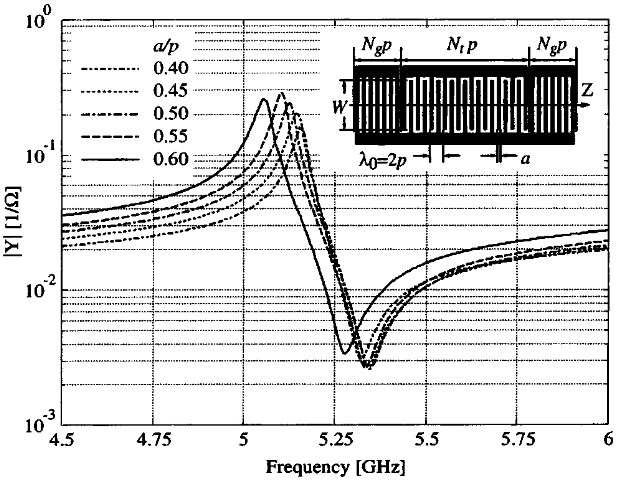

FIG. 1. Magnitude of admittance as a function of frequency for test resonators with the metallization ratio a/p as a parameter. Inset shows the layout of a synchronous SAW resonator, where W is aperture, p is pitch, a is finger width, N_g and N_t are the numbers of fingers in the reflector and interdigital transducer, respectively. The geometrical parameters for the test resonators are: $N_t = 201$, $N_g = 37$, $W = 15\ \mu\text{m}$, and $p = 0.6\ \mu\text{m}$. Effective Al thickness is 965 Å.

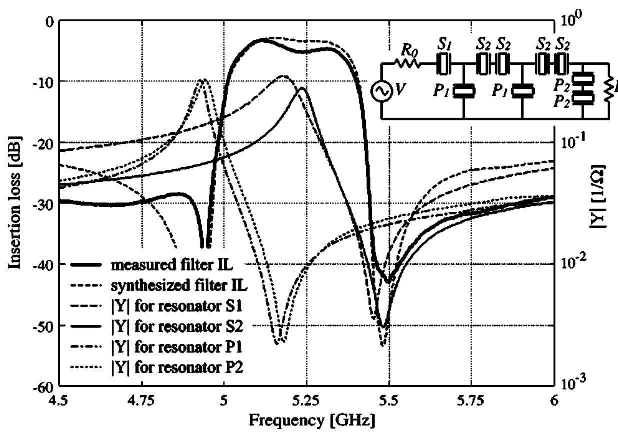

FIG. 2. Filter transmission response together with the magnitudes of the admittances for the series and parallel resonators for an effective Al thickness 965 Å. The inset shows the ladder filter configuration employed, where R_0 is the source and load resistance, S and P denote the series and parallel SAW resonators, respectively, and V is the amplitude of the applied voltage.

low-loss high-frequency wide band filter applications.

The losses of LLSAW propagating on a flat YZ-$LiNbO_3$ surface are quite high; for a metallized surface, the value 1.5 dB/λ has been computed by Grigorievski.[5] However, for LLSAW propagating in a periodic system of electrodes deposited on the substrate surface, the losses become significantly lower.[5–7] The electrode structure creates boundary conditions such that the coupling of LLSAW with the shear BAW becomes weak and the energy loss due to "supersonic" radiation of the shear BAW mode into the substrate is low. For the metallization ratio $a/p = 0.50$ and an aluminum (Al) electrode thickness of 8%, the attenuation value for LLSAW propagating in a periodic Al electrode grating is estimated to be on the order of 0.1–0.4 dB/λ. The high attenuation of LLSAW on a flat surface implies that LLSAW is only advantageous in structures which feature no breaks in periodicity, since the presence of a free surface inevitably causes a substantial increase in the losses.

Several test resonators with their operating frequencies above 5 GHz have been fabricated on YZ-$LiNbO_3$ to investigate the effects of the metallization ratio (parameter a/p) and the acoustic aperture W on the resonator performance. The layout and geometrical parameters of a synchronous resonator are described in the inset of Fig. 1. The measured magnitudes of the admittances for the test resonators are plotted in Fig. 1 for the metallization thickness 8% and varying metallization ratios. It can be seen that close to $a/p = 0.45$, the resonance and antiresonance frequencies are insensitive to small variations in a/p. This is advantageous for the fabrication yield, since an accurate control of the metallization ratio is challenging owing to the critical dimensions being rather close to the physical limits of optical lithography. One can also see that the resonance–antiresonance distance decreases with decreasing a/p.

The electrical connection of the synchronous LLSAW resonators employed in our prototype bandpass filter is shown in the inset of Fig. 2. The filter contains two different series resonators (S_1 and S_2) and two different parallel resonators (P_1 and P_2). The geometrical parameters of the LLSAW resonators in the filter are enumerated in Table I. Measured magnitudes of the admittances for the corresponding test resonators are plotted in Fig. 2 together with the measured filter transmission coefficient, S_{21}. The measurements are done in a 50 Ω environment directly on a wafer using a probe station and a network analyzer.

Figure 2 presents two filter responses: The solid filter curve is measured while the dashed curve is synthesized using the measured test-resonator responses. The measured filter features a center frequency of 5.20 GHz, the very wide 3 dB fractional bandwidth of 6.3% (equal to 327 MHz measured in absolute bandwidth), and a minimum insertion loss (IL) of 3.3 dB. Furthermore, the close-in suppression level is above 25 dB, which is an excellent value for a ladder filter in the 5 GHz frequency regime. The differences in the stopband are due to additional parasitics present in the measurement,

TABLE I. Geometrical parameters for the series and parallel resonators in the prototype ladder filter.

	Resonator			
Parameter	S1	S2	P1	P2
Pitch (p)	0.587 μm	0.581 μm	0.632 μm	0.629 μm
Metallization ratio (a/p)	0.50	0.50	0.50	0.50
Electrode thickness (h/λ_0)	7.9%	8.0%	7.4%	7.4%
Acoustic aperture (W)	50.0 μm	25.0 μm	25.0 μm	25.0 μm
No. of fingers (N_t)	201	215	175	201
No. of fingers (N_g)	20	20	20	20

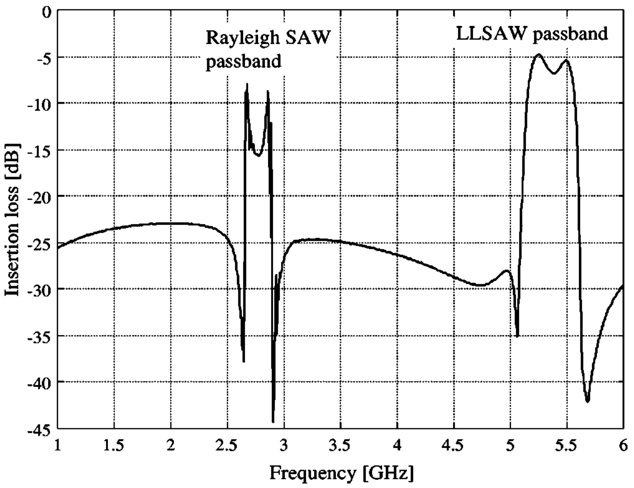

FIG. 3. Wide band filter transmission response for an effective Al thickness of 880 Å. The filter passband due to LLSAW occurs for frequencies above 5 GHz while the passband close to 2.75 GHz is due to the Rayleigh SAW.

e.g., via capacitive feedthrough. These parasitics can be influenced by the proper design of the filter layout. The notch present in the measured filter response in the middle of the passband is most likely due to underestimated parasitic capacitances from the signal input and output pads to the ground.

In the test-resonator responses of Fig. 2, it can be seen that at 5 GHz frequencies the aperture strongly influences the Q value at resonance, where there is a large current flowing through the resonator. As the aperture increases, the Q value decreases because of the increasing resistance of the narrow finger electrodes. It is fortunate that the Al finger thickness providing the lowest losses at resonance is relatively high ($h/\lambda_0 = 8\%$) since the losses due to electrode resistivity increase as the finger thickness decreases.

In addition to the LLSAW, YZ-cut $LiNbO_3$ also supports the Rayleigh SAW mode. This gives rise to an additional "passband" in the filter response at about half of the frequency of the passband due to LLSAW, as can be seen in the wide band filter transmission response in Fig. 3. Depending on the filter specifications, one may need to take measures to suppress this unwanted passband in actual applications. However, there is no third-harmonic LLSAW response since at the third-harmonic frequency the relative electrode thickness is very far above the optimum, causing strong attenuation of the LLSAW. Also, we have not detected any traces of the third-harmonic response of Rayleigh waves. Comparing the LLSAW filter responses for the effective Al thicknesses 965 Å (in Fig. 2) and 880 Å (in Fig. 3), the latter features a higher center frequency since the center frequency increases with decreasing Al thickness. The Al thickness 965 Å is closer to the optimum than 880 Å and, consequently, the resonator Q values are lower and the filter IL is higher for the latter thickness.

In conclusion, test resonators operating with the fast surface-wave mode, viz. LLSAW, have been fabricated on YZ-cut lithium niobate with operating frequencies above 5 GHz to investigate the dependence of synchronous LLSAW resonator performance on the metallization ratio and the acoustic aperture. Bandpass ladder filters with synchronous LLSAW resonators as the building blocks have also been fabricated on YZ-$LiNbO_3$ with a center frequency as high as 5.2 GHz. The prototype filter features a wide 3 dB bandwidth of 6.3% and a minimum insertion loss of 3.3 dB. With further optimization of the resonators and the filter layout, the filter performance appears acceptable for commercial WLAN applications.

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