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Surface-acoustic-wave devices for the 2.5–5 GHz frequency range based on longitudinal leaky waves

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The recently discovered "longitudinal leaky" surface acoustic wave on *YZ*-cut lithium niobate has been used to implement low-loss bandpass filters operating in the 2.5-GHz Bluetooth frequency range. The filter is of the ladder type, employing synchronous resonators as building blocks. Resonator *Q*-values above 300 have been measured. The filter features a center frequency of 2491 MHz, a minimum insertion loss of 3.5 dB, and a fractional 3-dB bandwidth as wide as 6.2%. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1573361]

Surface-acoustic-wave (SAW) filters operating on radio frequencies are key components in modern telecommunication systems, offering high performance in small size. The operating frequencies of wireless communication systems are being continuously increased to enable a higher bandwidth. Bluetooth, HiperLAN and other communication systems already utilize the 2–6-GHz frequency range. However, the fabrication of high-frequency SAW filters with center frequencies above 2 GHz using optical lithography has proven challenging. An increase in the center frequency of a fundamental-mode SAW filter can be obtained, in principle, either by decreasing the SAW wavelength or by increasing the SAW velocity. In practice, the resolution of the optical lithography process used in the mass fabrication of SAW devices limits the smallest period of the electrode structure in the interdigital transducer (IDT) used to excite the SAW. Hence, as a means of extending the operating frequencies of SAW devices, wave modes with high velocities are being actively searched.

As a method to increase the SAW velocity, layered lithium niobate/diamond/silicon structures have been reported.[1] In this layered structure, the extremely high velocity of an acoustic wave in diamond is exploited to achieve high-velocity SAW modes. In contrast, we use a special high-velocity SAW mode propagating in monocrystalline *YZ*-cut lithium niobate (*YZ*-LN) to implement high-frequency low-loss SAW filters.

It is known that the fastest acoustic waves in crystals are of the quasilongitudinal type. The velocity of longitudinal waves can be typically twice that of the Rayleigh SAW mode. Since the longitudinal wave alone cannot fulfill the boundary condition of zero stress on the surface, it is always coupled with the shear wave. Surface acoustic Rayleigh waves are widely used in different types of frequency filters for telecommunications equipment as the fundamental propagation mode. The wave consists essentially of a combination of longitudinal and shear displacements confined to the sagittal plane and fulfilling the boundary conditions. These two nonuniform components of the wave, strongly coupled through the boundary, decay exponentially inside the substrate and create the Rayleigh SAW. The propagation of the longitudinal wave along the surface is forbidden just because of this strong coupling; since the velocity of the longitudinal wave is higher than that of the shear wave, a longitudinal wave skimming along the surface would radiate shear waves into the bulk with amplitudes comparable with its own amplitude. This causes very strong attenuation, as all the wave energy is radiated within a distance comparable with a single wavelength. Such "surface resonances" were first described by Glass and Maradudin,[2] but the very high attenuation on the order of 10 dB/wavelength caused any attempt for the practical application of these waves to become impossible. It was recently found[3] that in some cuts of LN, this "supersonic" radiation of the shear component can be suppressed by using a periodic electrode system of definite geometry. Moreover, Grigorievski has shown[4] that similar waves exist in the classic *YZ*-cut of LN. The electrodes need to have a height close to one-quarter of the shear-wave wavelength.[5] These waves, called longitudinal leaky SAWs (LLSAWs), feature a velocity between those of the longitudinal and fast shear bulk acoustic waves (BAW). On *YZ*-LN, the phase velocity of LLSAW propagating in a periodic system of aluminum electrodes is about 6100 m/s, which is close to the velocity of the longitudinal BAW (≈7200 m/s) and about 1.8 times that of the Rayleigh SAW. On this sub-

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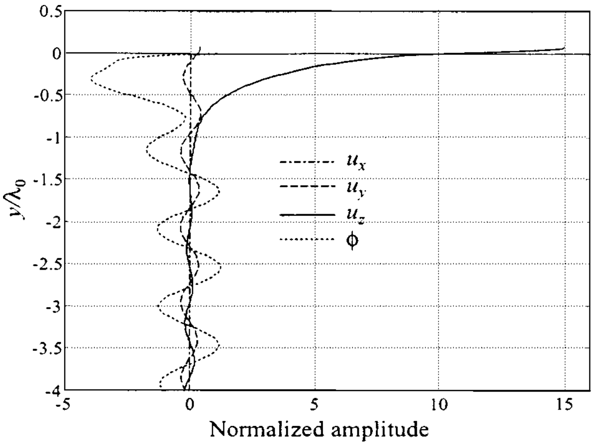

FIG. 1. Components of mechanical displacement and electric potential as functions of distance (y) from the substrate surface. Distance is in units of LLSAW wavelength λ_0 (at the center frequency of the IDT stopband). The y-component is decoupled; the longitudinal displacement component is dominating.

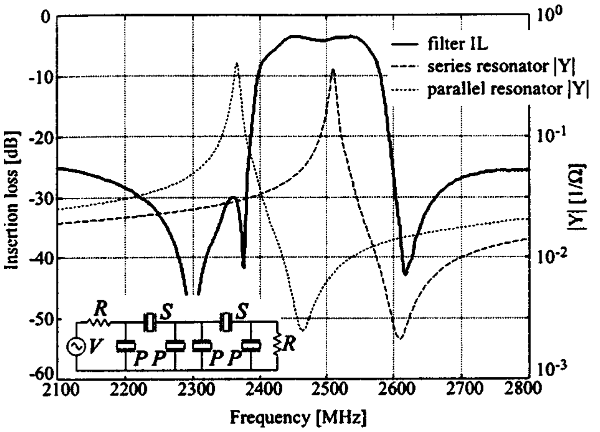

FIG. 3. Filter transmission response, together with the magnitude of admittance for series and parallel resonators. The inset shows the employed 2π ladder filter configuration, where R is the source and load resistance, S and P are the series and parallel SAW resonators, respectively, and V is the amplitude of applied voltage.

strate, LLSAW also features low loss and high coupling, rendering it suitable for high-frequency wideband filter applications.

We have implemented SAW resonators and filters in the 2.5-GHz frequency range, based on the LLSAW mode on *YZ*-cut lithium niobate. The finger-width of the electrodes in the resonator IDT is about 0.73 μm, which is easily fabricated with conventional optical lithography. Current optical lithography allows the fabrication of down to 0.3-μm-wide fingers, which for LLSAW devices implies a 5-GHz operating regime. In addition, LN is a widely used material and the *YZ*-cut is only weakly pyroelectric. Hence, mass fabrication with a high yield of SAW filters appears quite possible for the Bluetooth band of 2.45-GHz frequencies.

The propagation loss of LLSAW in LN depends on the crystal cut as well as on the dimensions of the electrodes constituting the IDT.[3,4,6] In particular, the relative thickness of the Al electrodes providing the lowest loss on YZ-LN is relatively large, about 8% for a metallization ratio of 0.6.[3,4,6] In YZ-LN, the LLSAW propagates along the direction of the crystal Z-axis and the surface normal is in the direction of the crystal Y-axis; the displacements of the LLSAW are in the *YZ*-plane (sagittal plane). For this cut, the shear wave with polarization perpendicular to the sagittal plane is decoupled. Hence, instead of two shear waves, the attenuation of LLSAW on YZ-LN is due only to the radiation of the shear wave polarized in the sagittal plane into the bulk of the substrate. Figure 1 illustrates the spatial distribution of the components in the LLSAW mode. One can see that the dominating longitudinal component decays exponentially into the depth of the substrate. Simulations and measurements show that the optimum thickness providing the highest resonator Q-value decreases with the metallization ratio, and that the Q-value of a synchronous LLSAW resonator depends rather strongly on the Al thickness.

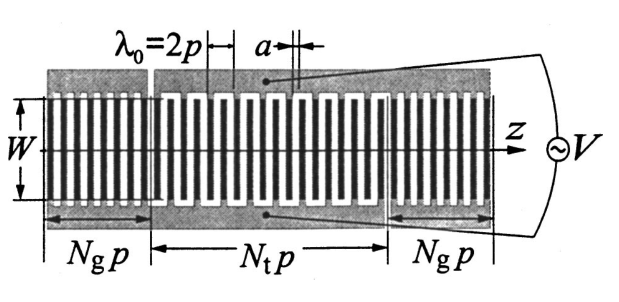

FIG. 2. Top view of a synchronous one-port SAW resonator, illustrating the geometrical parameters (schematic). In the figure, W is aperture, p is pitch, a is the gap between the electrodes, N_g and N_t are the numbers of electrodes in the reflectors and the IDT, respectively, and V is the amplitude of the applied voltage.

Figure 2 is a schematic drawing of the synchronous resonator, describing the relevant geometrical parameters. The Al thickness was 2030 Å. For a bandpass filter, a 2π-ladder connection of the synchronous one-port LLSAW resonators is used, shown in the inset of Fig. 3. The two series (S) resonators are equal, as are the four parallel (P) resonators. The geometry of the resonators is summarized in Table I.

The on-wafer resonator and filter measurements were carried out using a network analyzer in a 50-Ω environment. The resonator performance determined from the measured responses is presented in Table II. The Q-values at resonance (r) and antiresonance (ar) were determined through fitting a parabola to the conductance and resistance peaks, respectively, and using the definition $Q=f/\Delta f$, where Δf is the full width at half-maximum value of the peak. The Q-values at resonance are about twice those at the antiresonance.

The measured filter transmission coefficient S_{21} versus frequency is shown in Fig. 3, together with the magnitude of the admittance of the test resonators. The filter features a center frequency of 2.491 GHz, a minimum insertion loss of 3.5 dB, and the 3-dB bandwidth is 154 MHz, equal to a 6.2%

TABLE I. Geometrical parameters for the series and parallel resonators.

Parameter	Series resonator	Parallel resonator
Pitch (p)	1.225 μm	1.325 μm
Metallization ratio ($1-a/p$)	0.60	0.60
Metallization thickness (h/λ_0)	8.29%	7.66%
Aperture (W)	24 μm	24 μm
No. of fingers N_t	201	241
No. of fingers N_g	37	37

TABLE II. Performance figures of the series and parallel resonators.

Parameter	Series resonator	Parallel resonator
Q_r	281	271
Q_{ar}	117	111
f_r	2510 MHz	2366 MHz
f_{ar}	2608 MHz	2462.5 MHz
r-a-r	3.8%	4.0%

fractional bandwidth. The close-in stopband suppression is above 20 dB.

In conclusion, a high-frequency bandpass ladder filter based on the longitudinal leaky SAW has been fabricated on *YZ*-cut lithium niobate. The synchronous resonators used in the filter feature *Q*-values in excess of 250 at resonance. The filter exhibits a center frequency of 2.49 GHz and a 3-dB bandwidth of 6.2%. In this first iteration of the design, a minimum insertion loss of 3.5 dB is achieved. With the low insertion loss of the implemented filter, perspectives for LLSAW ladder filters with center frequencies as high as 5 GHz seem promising.

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[1] E. Dogheche, V. Sadaune, X. Lansiaux, D. Remiens, and T. Gryba, Appl. Phys. Lett. **81**, 1329 (2002).
[2] N. E. Glass and A. A. Maradudin, J. Appl. Phys. **54**, 796 (1983).
[3] A. Isobe, M. Hikita, and K. Asai, IEEE Trans. Ultrason. Ferroelectr. Freq. Control **46**, 849 (1999).
[4] V. I. Grigorievski, *Proc. IEEE Ultrasonics Symposium 2000* (IEEE, New York, 2000), p. 259.
[5] V. Plessky, T. Makkonen, and M. M. Salomaa, *Proc. IEEE Ultrasonics Symposium 2001* (IEEE, New York, 2001), p. 239.
[6] T. Makkonen, V. Plessky, V. I. Grigorievski, L. Kopp, M. Solal, W. Steichen, and M. M. Salomaa, *Proceedings of the IEEE Ultrasonics Symposium 2002* (IEEE, New York, 2002), p. 305.