Dual-mode Shear Horizontal / Rayleigh-like surface-acoustic-wave configuration on lithium niobate 64° Y-cut

F. Lunardelli [2,3], M.Agostini [2], E. Corradi [3] and M.Cecchini [1]

[1]NEST, Istituto Nanoscienze - CNR, Piazza S. Silvestro 12, 56127 Pisa, Italy; marco-cecchini@cnr.it;
[2]NEST, Scuola Normale Superiore, Piazza San Silvestro 12, 56127 Pisa, Italy; francesco.lunardelli@sns.it, elena.corradi@sns.it
[3]INTA srl, Via Nino Pisano 14, 56122 Pisa, Italy; m.agostini@intasystems.net

The Idea

A key challenge to enhance the performance of biosensors based on surface acoustic waves (SAW) is the capability of exciting different acoustic modes in the same substrate. [1][2] In our research, we investigate the SAW characteristics of the 64° Y-cut lithium niobate (LN) substrate.
This substrate is particularly effective in generating shear horizontal SAW (SH-SAW) along the crystal's X-axis, characterized by a strong electromechanical coupling coefficient k^2= 11.3% and a remarkably high propagation velocity 4474 m/s. [3]

We have developed and tested a SAW device based on a 64° Y-cut lithium niobate (LN) substrate to explore and characterize the different acoustic modes that can be excited within this specific substrate. Our research particularly focused on the potential to generate wave types other than SH-SAWs using interdigital transducers (IDTs) oriented differently from the X-axis.
To achieve this, we conducted:

- Finite Element Simulations (FEM)
- Electromechanical Characterization of the devices
- Acoustic-Streaming Analysis
- Tested the responses to temperature variation (temperature coefficient of frequency TCF)

FEM Simulations

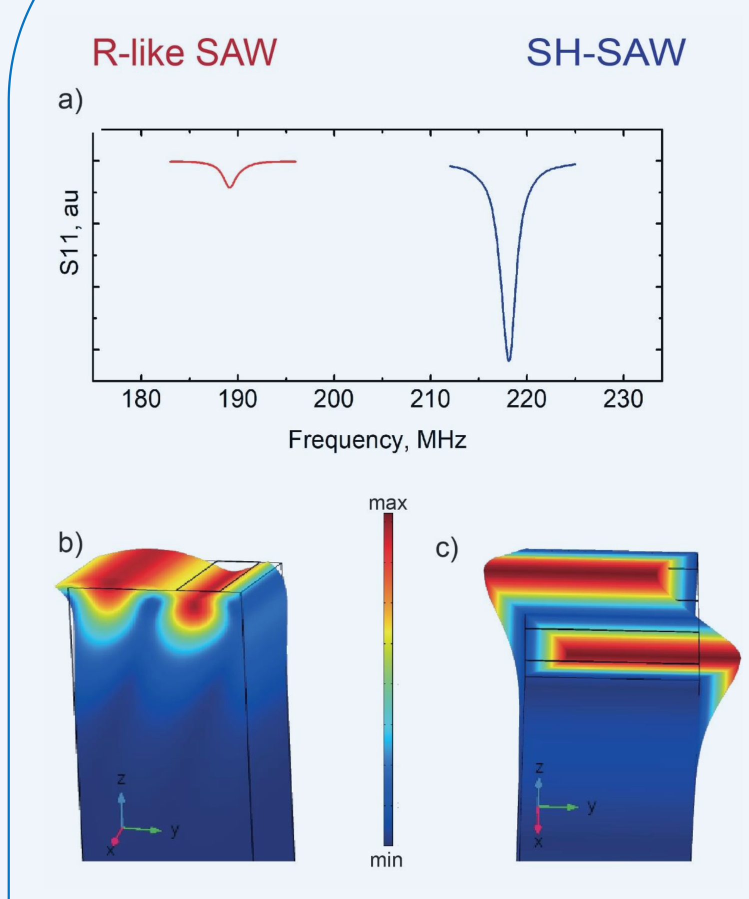


Fig.1 a) S11 spectra of R-like SAW at 189.2 MHz and SH-SAW at 218.1 MHz. b),c) 3D unit cell models representing the displacement of R-like SAW and SH-SAW.

FEM simulations of unit cell models, highlighted the feasibility of exciting two distinct acoustic modes on 64° Y-cut LN using two perpendicularly oriented IDTs.

The conventional setup with IDT along X-axis generates the well-known SH-SAW with propagation velocity in the range of 4400 m/s.

On the other hand, a perpendicular IDT configuration, yielded to a wave mode characterized by a strong component normal to the surface similarly to Rayleigh SAW, with propagation velocity of 3700 m/s.

Substrate	Wave	X displacement	Y displacement	Z displacement
64° Y-cut LN	SH-SAW	13%	62%	25%
64° Y-cut LN	R-like-SAW	1%	45%	54%
128° Y-cut LN	R-SAW	5%	36%	59%

Tab.1 Summary of the FEM analysis of the polarization at the resonance frequencies. We reported data obtained with 128° Y-cut LN as substrate (optimal configuration for R-SAW excitation).

Device Fabrication

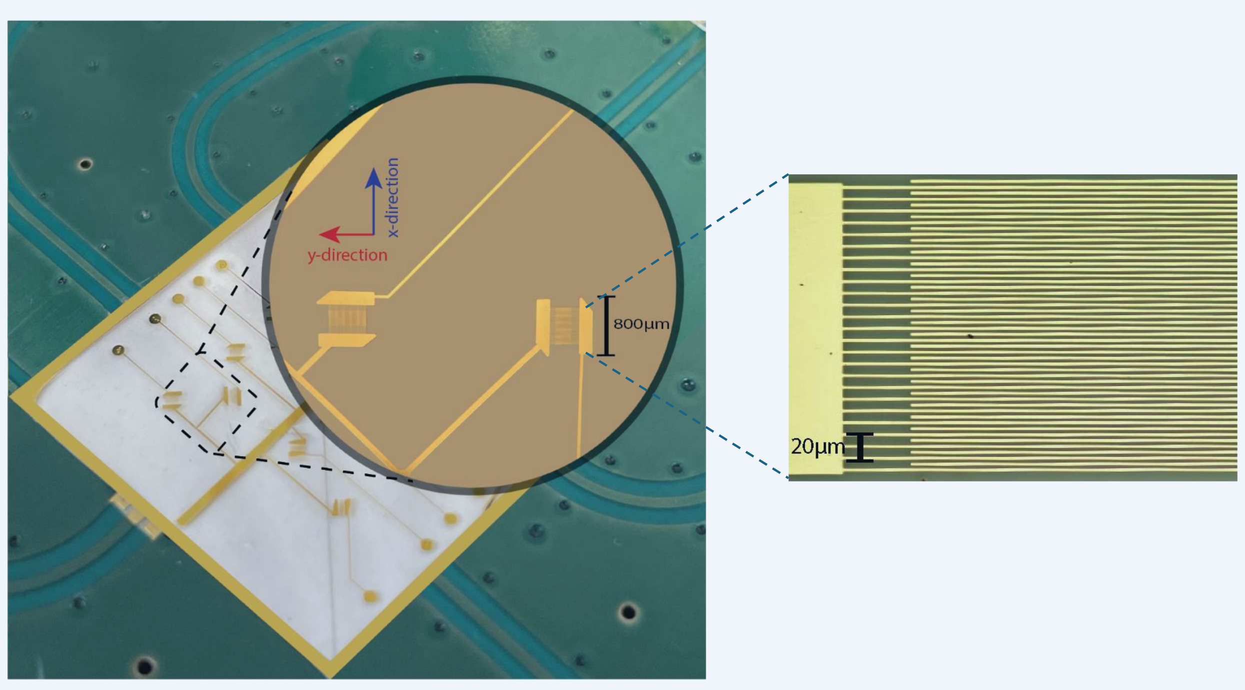


Fig.2 Optical microscope images depict the fabricated device

Via optical lithography we patterns on 64° Y-cut LN substrate two types of IDTs. Each IDT consists of 30 finger pairs with a 50% metallization ratio and electrodes width of 5 µm. The acoustic aperture for each IDTs is 250 µm. The electrodes are made of gold (Au) and have a thickness of 100 nm.
To explore different acoustic modes one IDT is oriented along the X crystallographic axis and the other in the perpendicular direction, corresponding respectively to the x-direction and y-direction of our coordinate system.

Electromechanical Characterization

We performed electrical characterizations of the device using a Vector Network Analyzer (VNA). The IDT oriented along the X-axis produces a resonance in the S11 signal at 217.8 MHz, representing a SH-SAW travelling at 4356 m/s. The system with the perpendicularly oriented IDT presents a resonance frequency at 190.3 MHz, indicative of a SAW travelling at 3806 m/s.

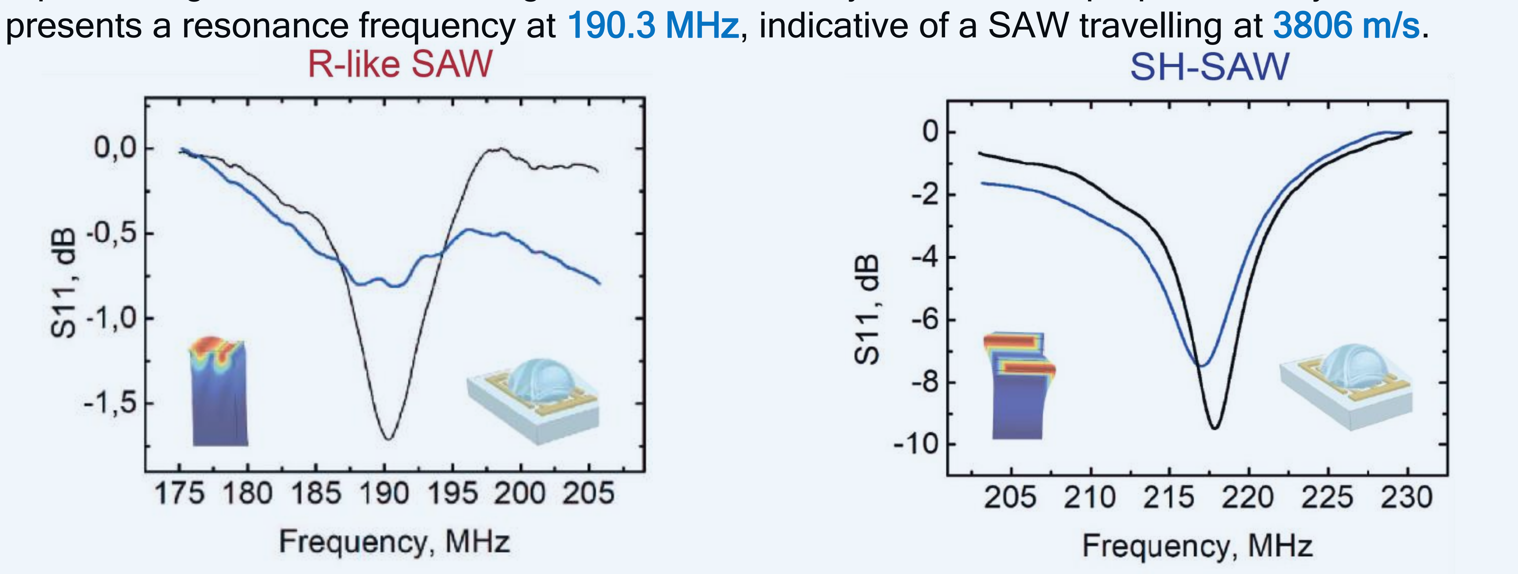


Fig.3 VNA characterization of the two acoustic mode. Black line represents the S11 signal in dry environment while blue line represents the changes in the resonance spectra when the IDTs were covered with a 2 µl droplet of DI water.

The mechanical analysis via laser doppler vibrometer (LDV) highlight the characteristics of the dual modes.

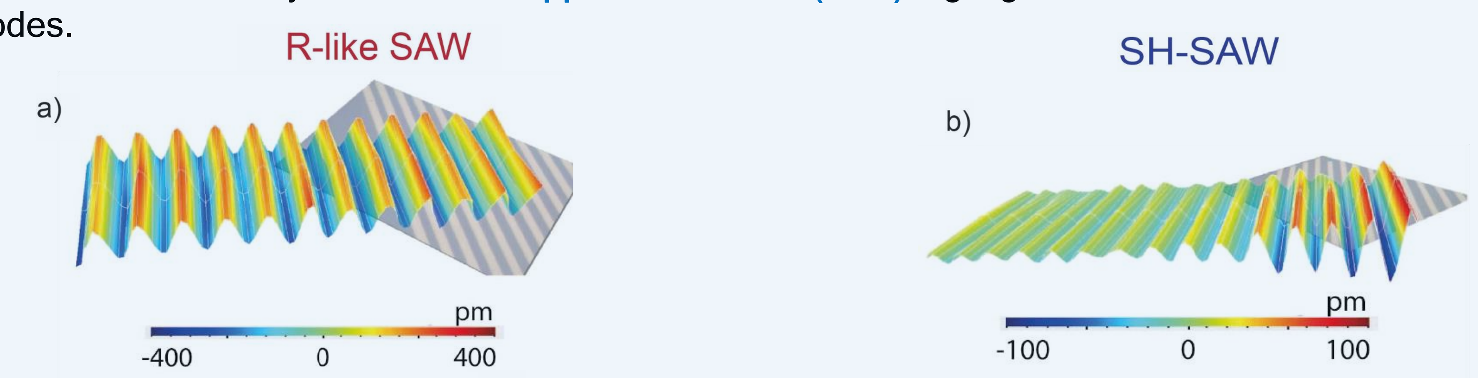


Fig.4 a) R-like SAW displayed a higher normal displacement and no-leaky propagation. b) SH-SAW present a smaller out-of-plane displacement and a typical leaky-SAW damping.

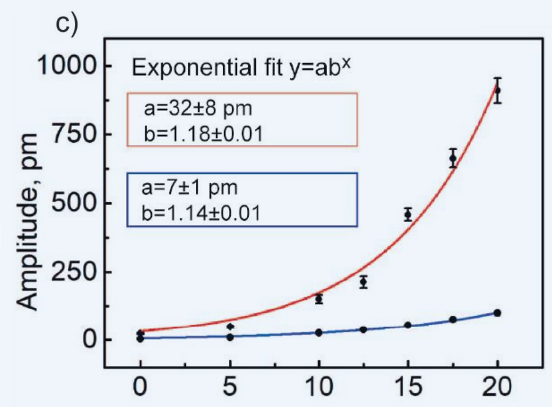


Fig.4 c) Exponential trend of the amplitudes as a function of the applied RF power.

Acoustic-Streaming Analysis

Acoustic streaming experiments were performed using a droplet containing a solution of latex beads in a droplet of DI water. The movement of the latex beads, which correlates with fluid motion, was recorded with high-speed camera at 555 fps.

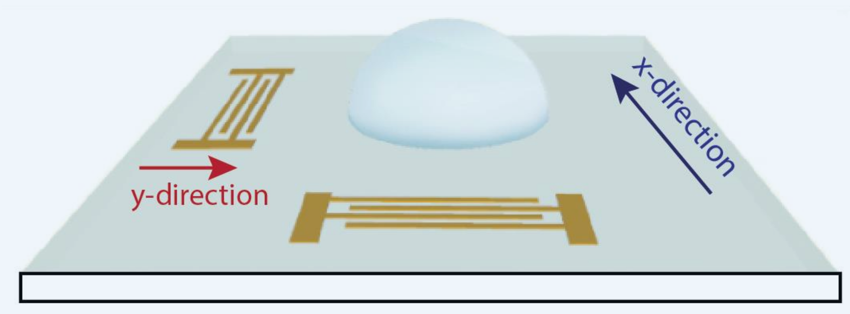
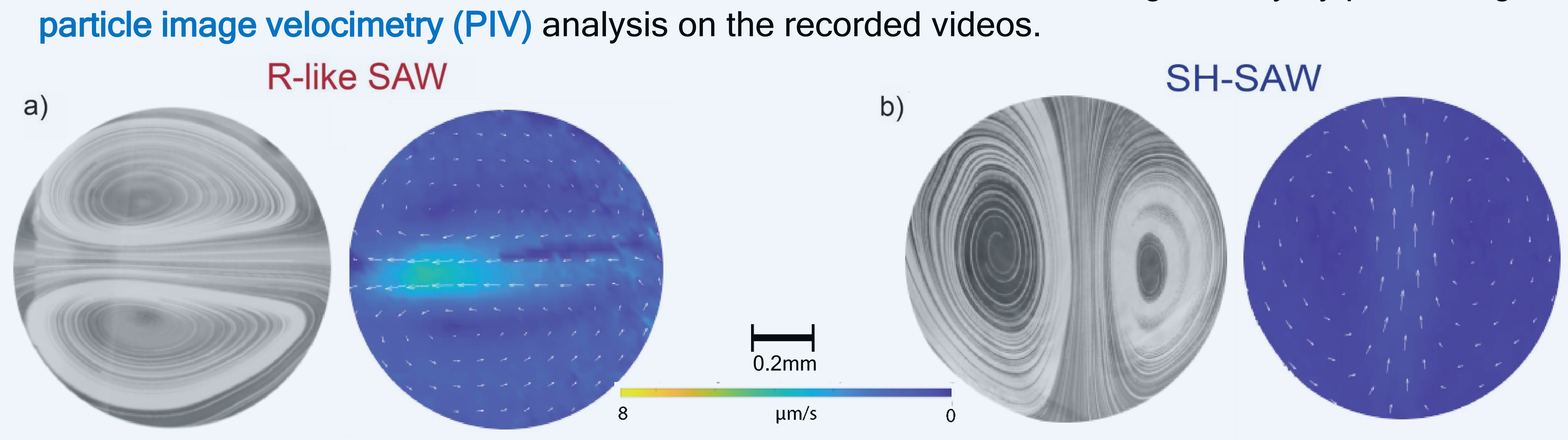


Fig.5 A 0.5 µL droplet was placed in front of the IDTs to analyze SH-SAW and R-like SAW streaming.

We reconstructed the induced streamlines and determined the streaming velocity by performing particle image velocimetry (PIV) analysis on the recorded videos.



Applied Power [dBm]	Average streaming velocity induced by SH-SAW [µm/s]	Average streaming velocity induced by R-like-SAW [µm/s]
0	41±2	370±20
10	450±20	2700±100
15	660±30	11400±500

Fig.6 a),b) PIV reconstruction of streamlines and of the velocity field induced by R-like-SAW and SH-SAW with a power of 0 dBm. Tab.2 Average streaming velocities within the droplet, as determined by PIV analysis, in relation to the applied power.

Conclusions

In conclusion, we have discovered a new configuration with IDTs oriented perpendicularly to X-axis, which can excite Rayleigh-like SAW. This characteristic makes the 64° Y-cut lithium niobate a promising substrate for dual-mode systems capable of carrying out sensing, mixing, and simultaneous detection in different environments (wet and dry).
The significant advantage of using lithium niobate lies in the substantial increase in the electromechanical coupling coefficient k^2 compared to other substrates.

	Principal component of displacement	Damping along the propagation direction	Damping in liquid	Acoustic-streaming	TCF
SH-SAWs	In plane, parallel to the propagation direction	Leaky	Low attenuation in liquid	Generation of mild induced acoustic streaming	-68.5 ± 0.4 ppm/°C
R-SAWs-like	Normal to the surface	Not leaky	High attenuation in liquid	Efficient generation of induced acoustic streaming	-84 ± 1 ppm/°C

Tab. 3. Complete characterization of the two acoustic modes

References

[1] Kogai T, Yatsuda H. Liquid sensor using SAW and SH-SAW on quartz. Proceedings - IEEE Ultrasonics Symposium. 2006.

[2] Li S, Bhethanabotla VR. Design of a Portable Orthogonal Surface Acoustic Wave Sensor System for Simultaneous Sensing and Removal of Nonspecifically Bound Proteins. Sensors (Basel). 2019

[3] Yamanouchi K, Shibayama K. Propagation and Amplification of Rayleigh Waves and Piezoelectric Leaky Surface Waves in LiNbO3. J. Appl. Phys. 1972

Contacts:

/in/francesco-lunardelli

/profile/Francesco_Lunardelli3