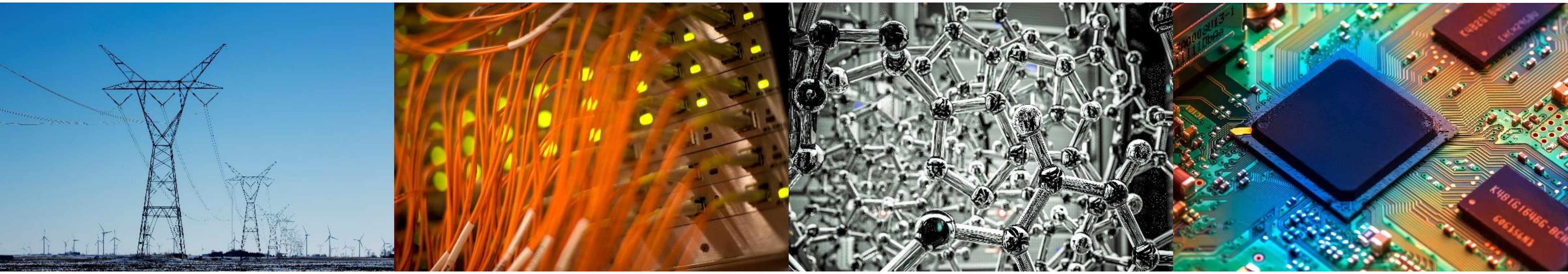
IEEE INTERNATIONAL CONFERENCE ON WIRELESS FOR SPACE AND EXTREME ENVIRONMENTS 2018

Extremely Low-Loss Lithium Niobate Acoustic Devices for Zero Power Signal Processing

Prof. Songbin Gong

Presented at Passive-Wireless-Sensor-Technology-Workshop 12.11.2018



ILLINOIS
Electrical & Computer Engineering
COLLEGE OF ENGINEERING

ILIRM Illinois Lab of Integrated RF Microsystems

Outline

- Motivation and Applications
- Acoustic Signal Processing in LN Thin Films
- Resonator-based Impedance Transformer
- Delay Line-based Chirp Compressor
- Conclusion and Acknowledgement

Promising Applications

5G

Massive Internet of Things (mMTC)

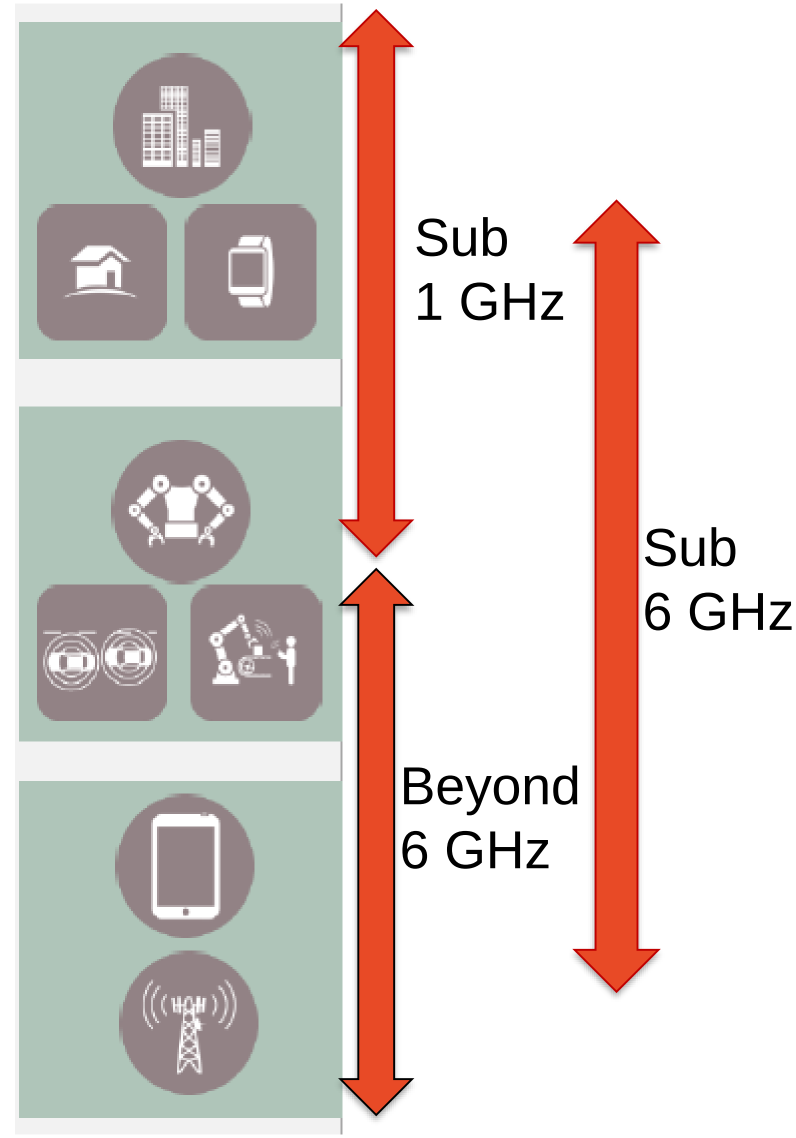
- Low cost
- Ultra low energy
- Broad coverage
- High density
- Security

Mission critical (URLLC)

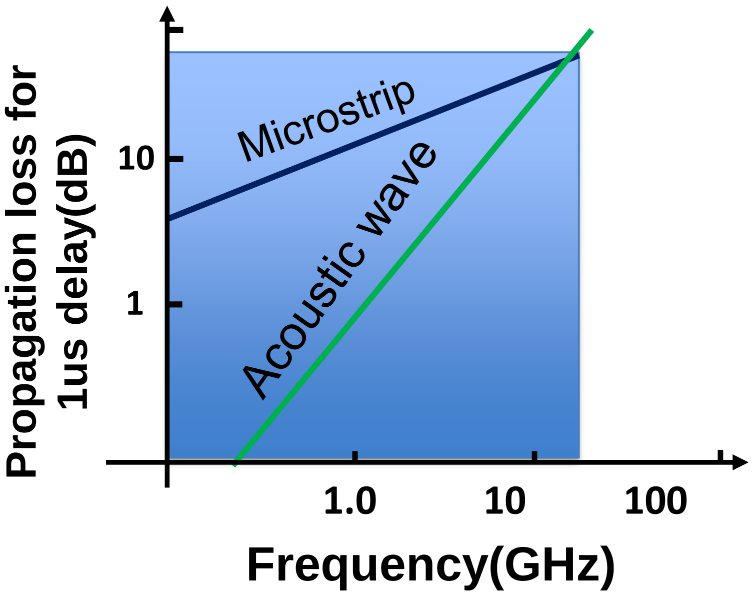
- Ultra low latency
- High reliability
- Safety & security
- High availability

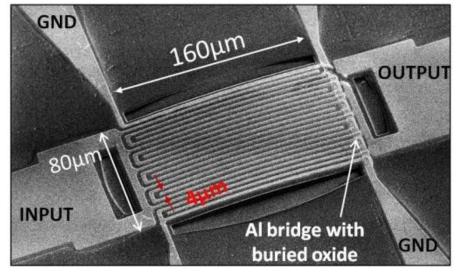
Enhanced Mobile Broadband (eMBB)

- High data rates
- Extreme capacity
- Uniformity
- Security

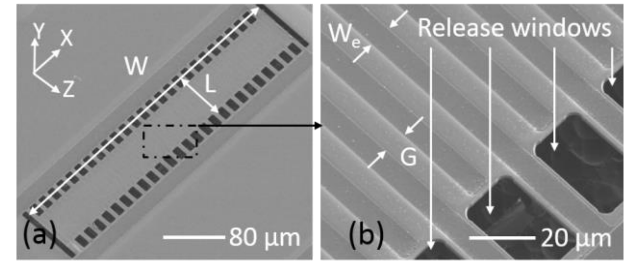


Acoustic Domain Signal Processing

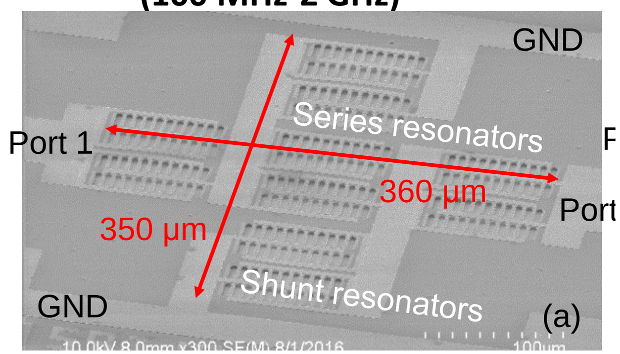




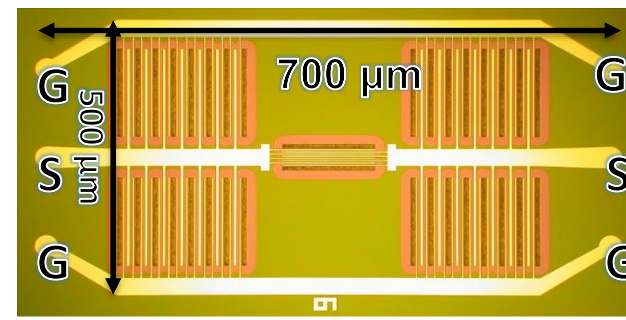
High Q and large coupling
RF-MEMS resonators, 2013
(100 MHz-2 GHz)



High frequency and high FoM
RF-MEMS A1 resonators, 2018 (2-30 GHz)

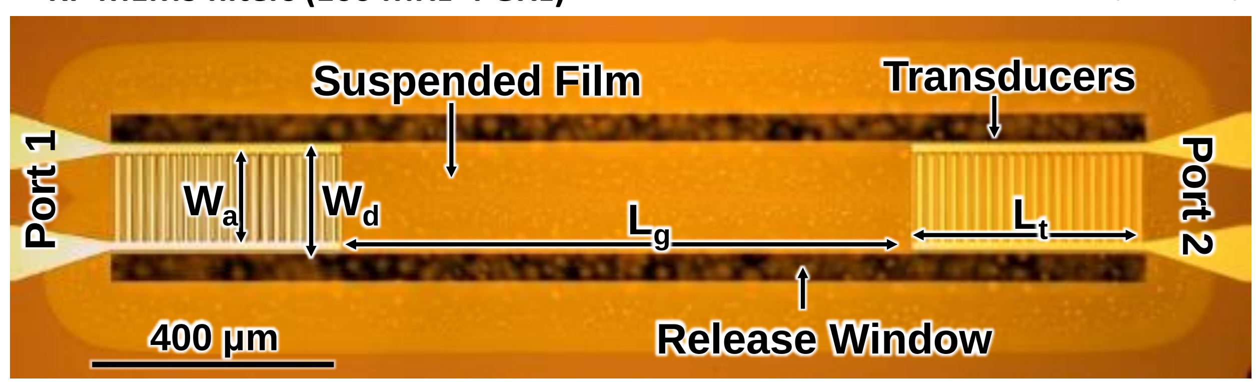


Wideband and low IL
RF-MEMS filters (100 MHz-4 GHz)



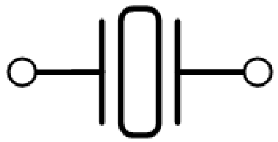
High frequency
RF-MEMS A1 filters, 2018 (10 GHz)

- Orders of magnitude smaller size compared to EM counterparts
- Lower propagation loss in waveguides and higher Qs

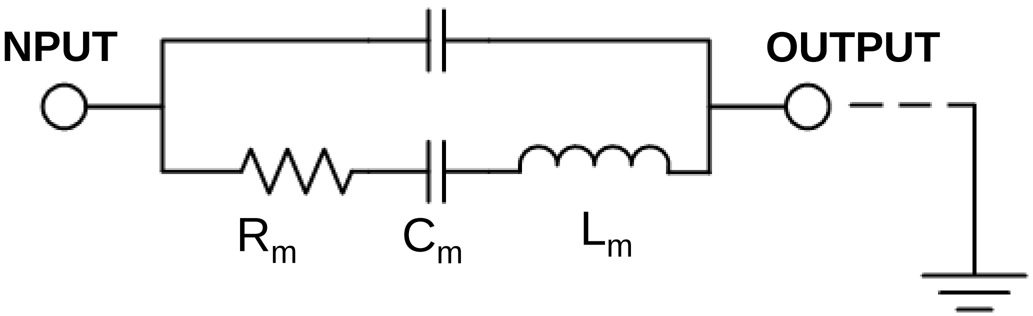


1dB IL acoustic delay lines, 2018 (1 GHz)

FoM of Acoustic Devices

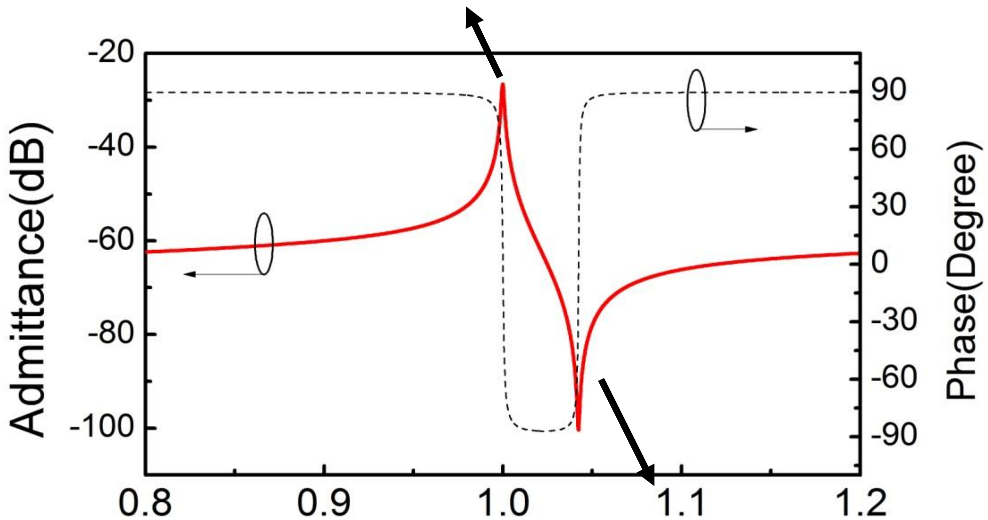


Circuit symbol for acoustic resonators



Equivalent circuit model for acoustic resonators

$$f_s = \frac{1}{2\pi}\frac{1}{\sqrt{L_m C_m}}$$



$$f_p = \frac{1}{2\pi}\sqrt{\frac{1}{L_m C_m} + \frac{1}{L_m C_0}}$$

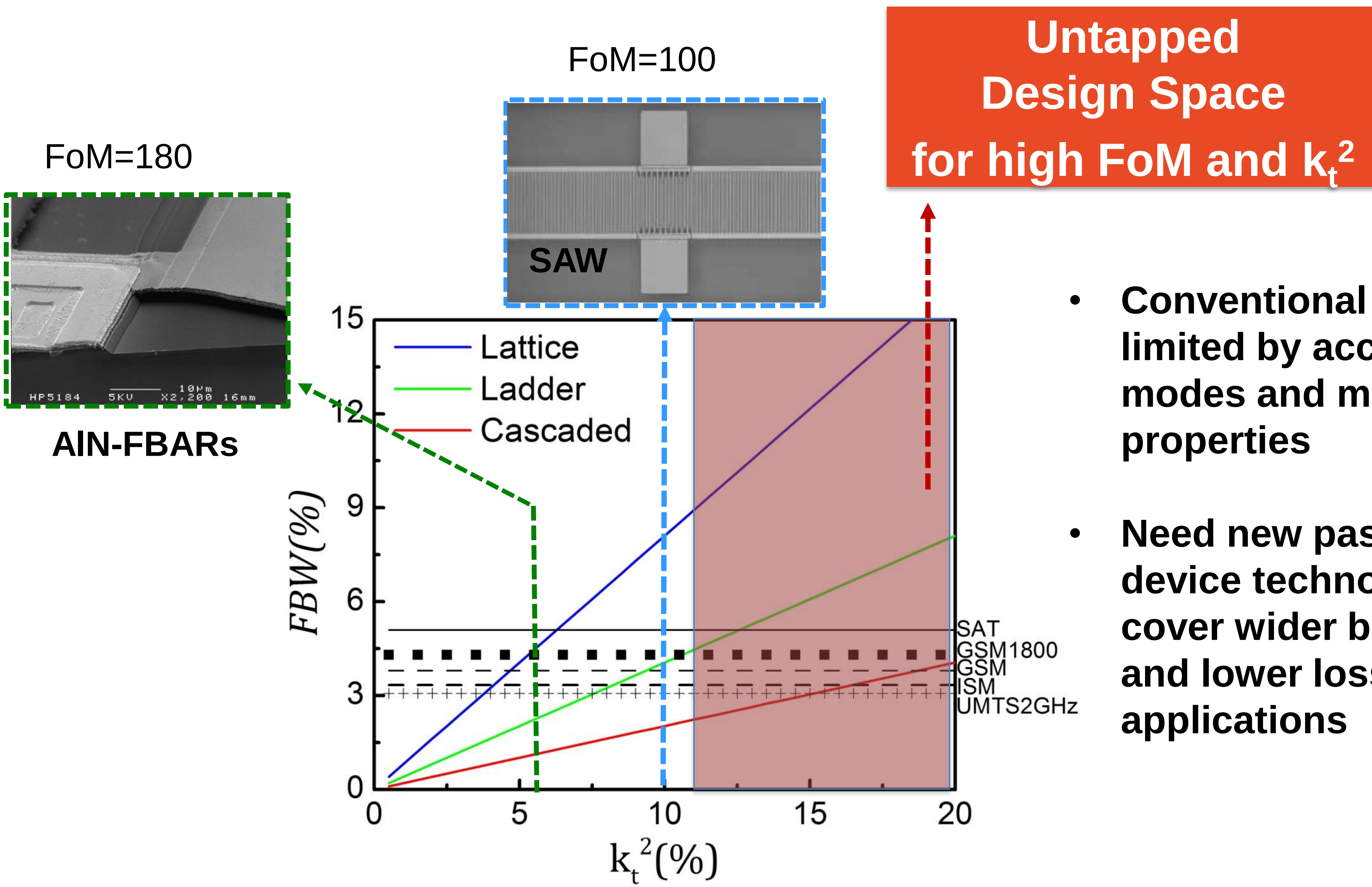
$$R_m = \frac{\pi^2}{8}\frac{1}{\omega_s \boxed{C_0}}\frac{1}{\boxed{k_t^2 Q}}$$

$$k_t^2 = \frac{Stored\_Mech\_Energy}{Stored\_Elect\_Energy} = \frac{\pi^2 C_m}{8C_0}$$

$$Q = 2\pi\frac{E\_Stored/cycle}{E\_Dissipated/cycle}$$

$$FoM = k_t^2 Q$$

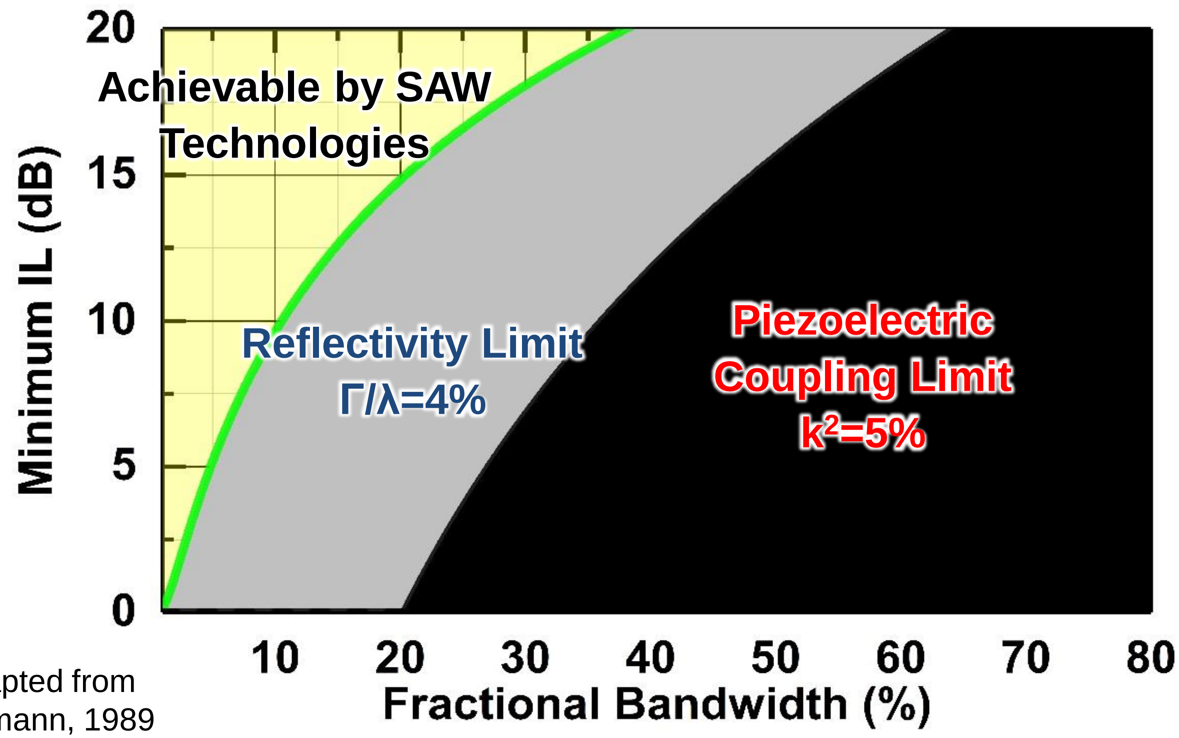
Performance Bounds of SOA



- **Conventional devices limited by accessible modes and material properties**
- **Need new passive device technology to cover wider bandwidth and lower loss applications**

Performance Bounds of SOA

Reindl, 2001

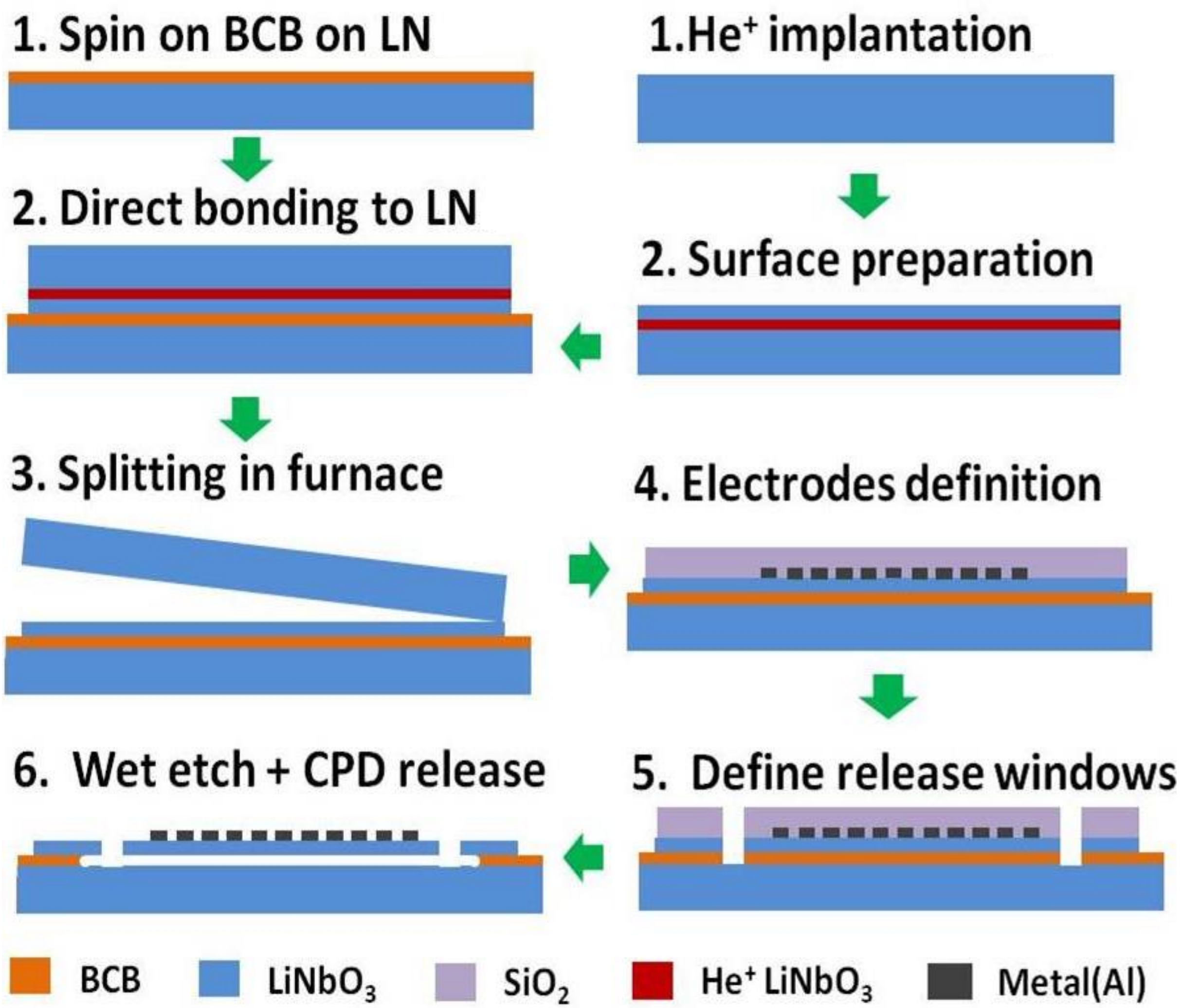


Adapted from Hartmann, 1989

- Piezoelectric coupling coefficient (k^2) of transducer
- Attainable reflectivity in embedded reflectors

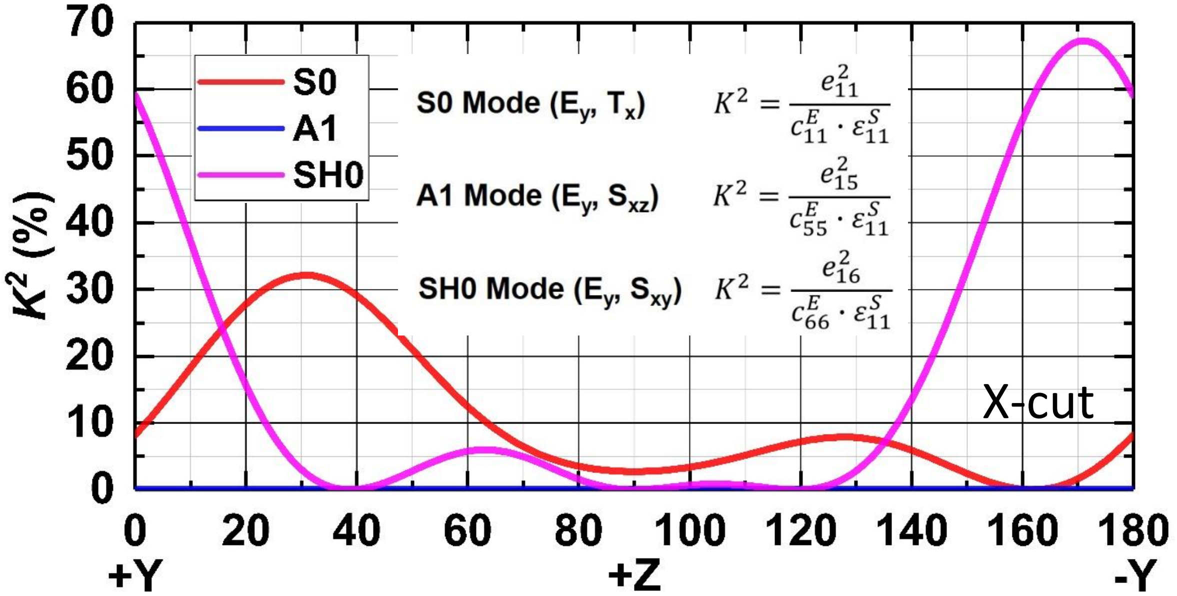
Need a new piezoelectric platform to break the conventional trade-offs

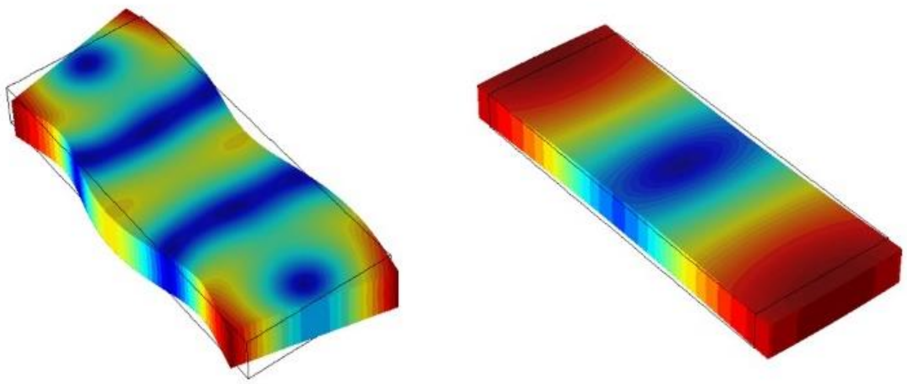
Lithium Niobate Thin Film Devices



- Ion slicing technique
- Bulk quality thin films of various LN cuts on a carrier substrate
- Suspended resonant and waveguiding structure on chipscale
- Engineerable dispersion and highly scable in frequency

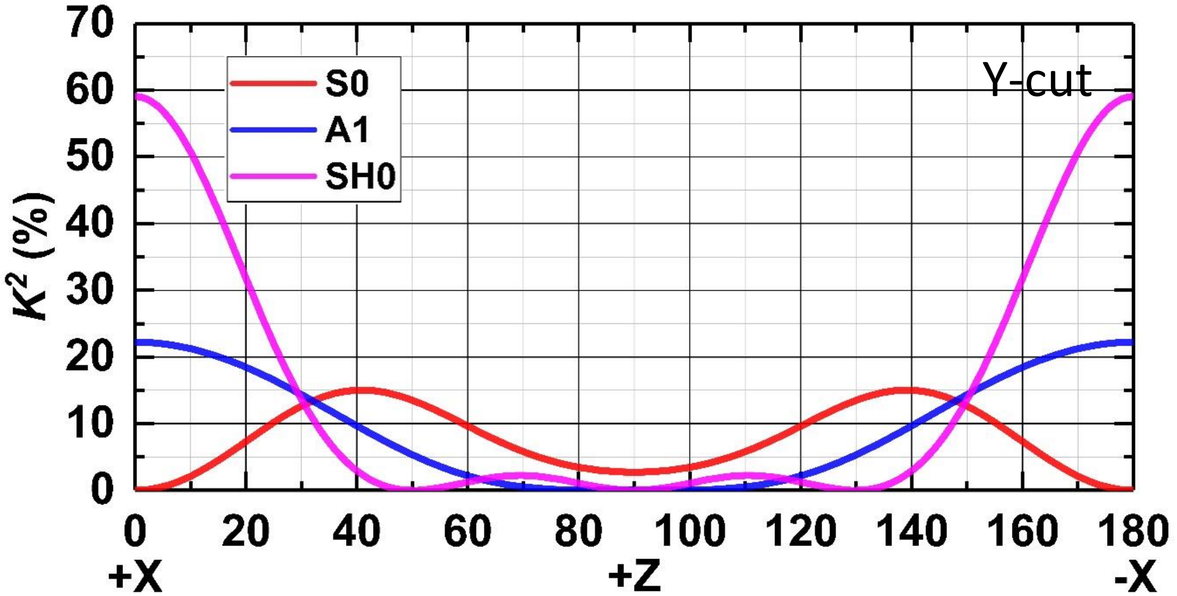
Acoustic Modes in LN Films





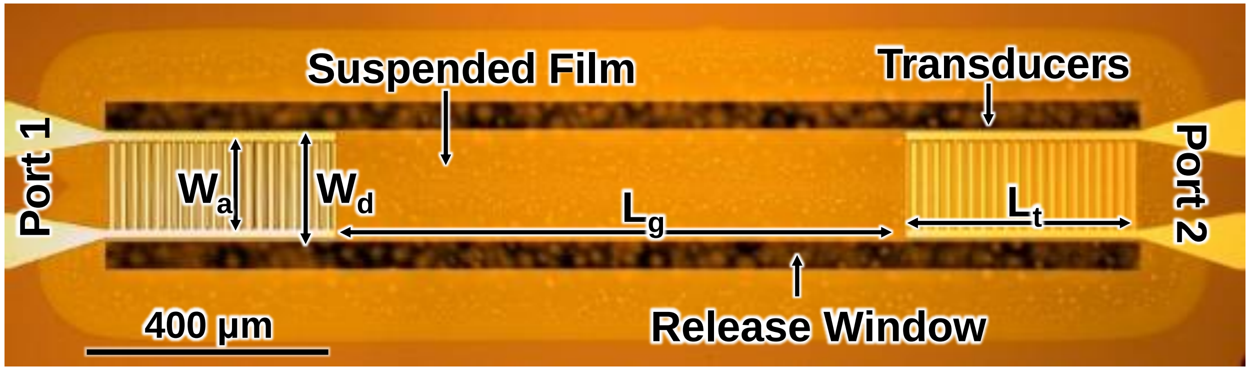
(a) Shear Horizontal mode

(b) Symmetrical lateral mode



- Various high K^2 modes accessible in various cuts
- Wide range of phase velocity for superior frequency scaling
- Propagation in single crystal films promises low loss and high Q

Acoustic Waveguiding in LN Films



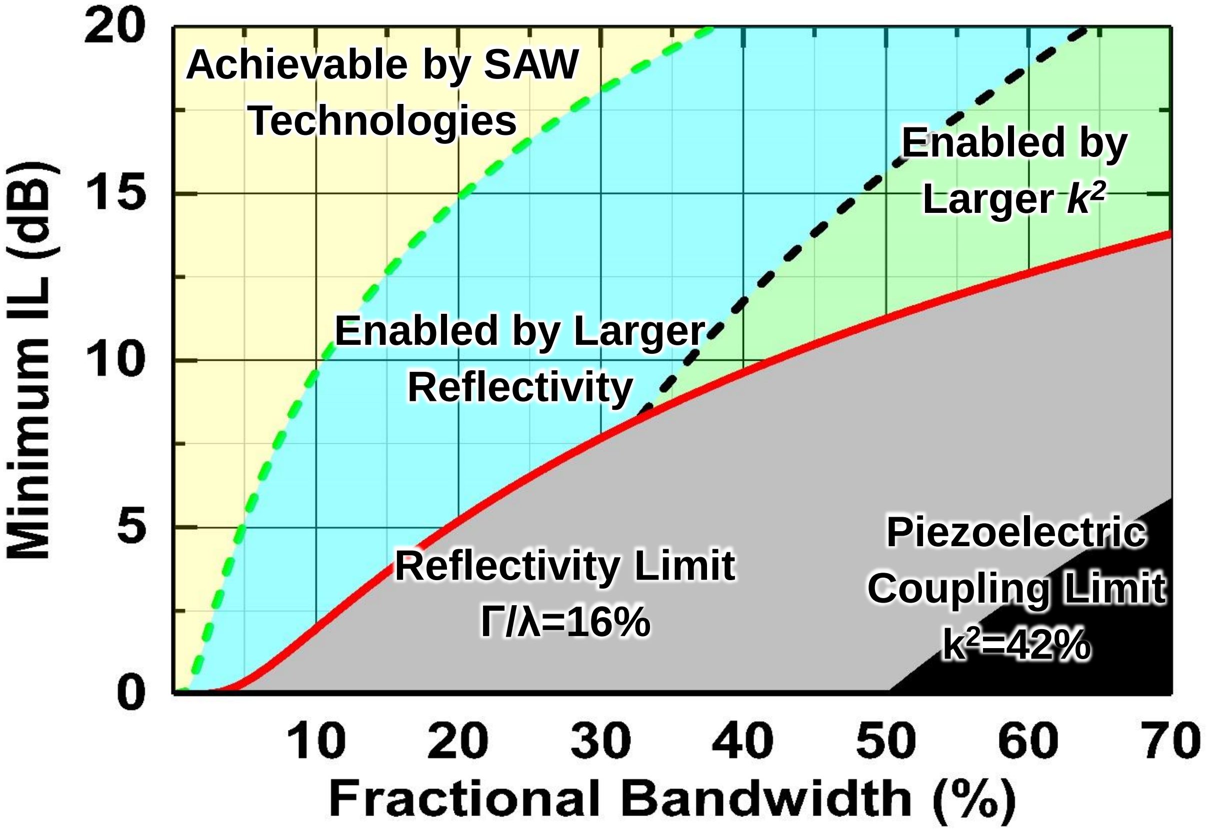
Overcome limitation imposed by piezoelectric coupling:

Larger k^2 → better FBW-IL tradeoff

Overcome limitation arising from moderate reflectivity:

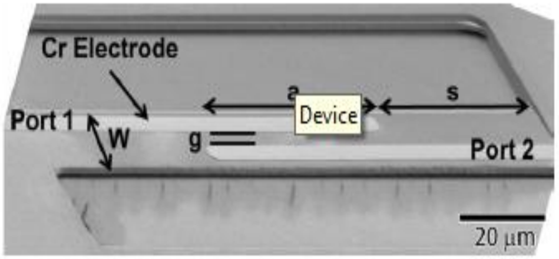
Larger k^2 → larger Γ_e

Thin-film structure → larger Γ_m



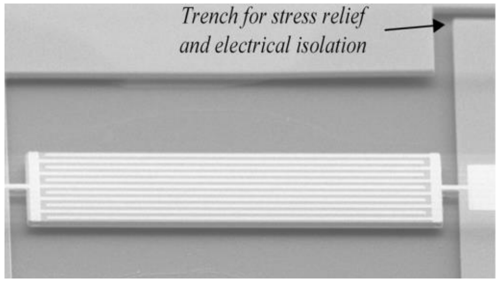
Development of LN Thin Films Devices

SH0 mode device



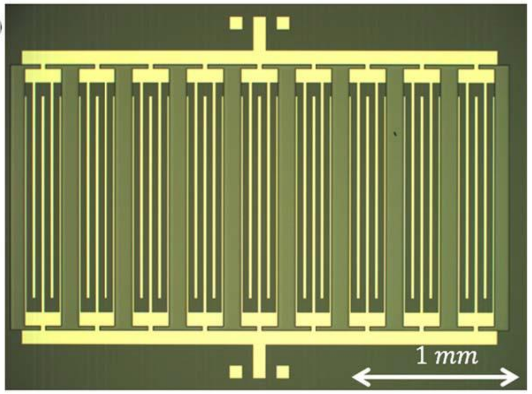
k_t^2=23.6%, Q=2200, FoM=420
X-cut, -10° to –Y, 350 MHz
By R. H. Olsson et. al. Sandia

S0 mode device



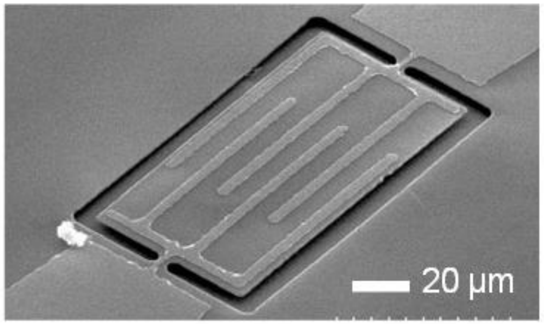
k_t^2=12.3%, Q=2115, FoM=110
Y-cut, 0° to Z, 800 MHz
By S. Bhave, et. al. Purdue Univ

S0 mode device



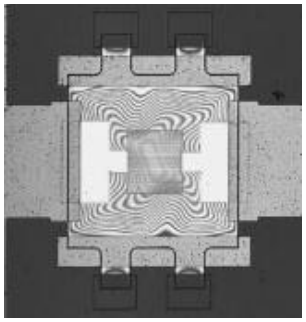
k_t^2=30.5%, Q=5110, FoM=1560
X-cut, 30° to X, 50 MHz
By G. Piazza, et. al. Carnegie Mellon

SH0 mode device



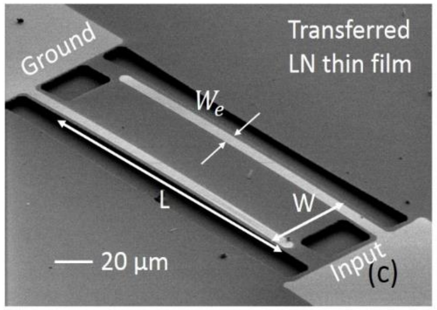
k_t^2=21.5%, Q=1527, FoM=320
X-cut, -10° to -Y, 0.5 GHz
By S. Gong, et. al. UIUC

A1 mode device



k_t^2=18%, Q=N/A
Y-Cut, 4.5 GHz
By M Kadota et. Al.

A1 mode device

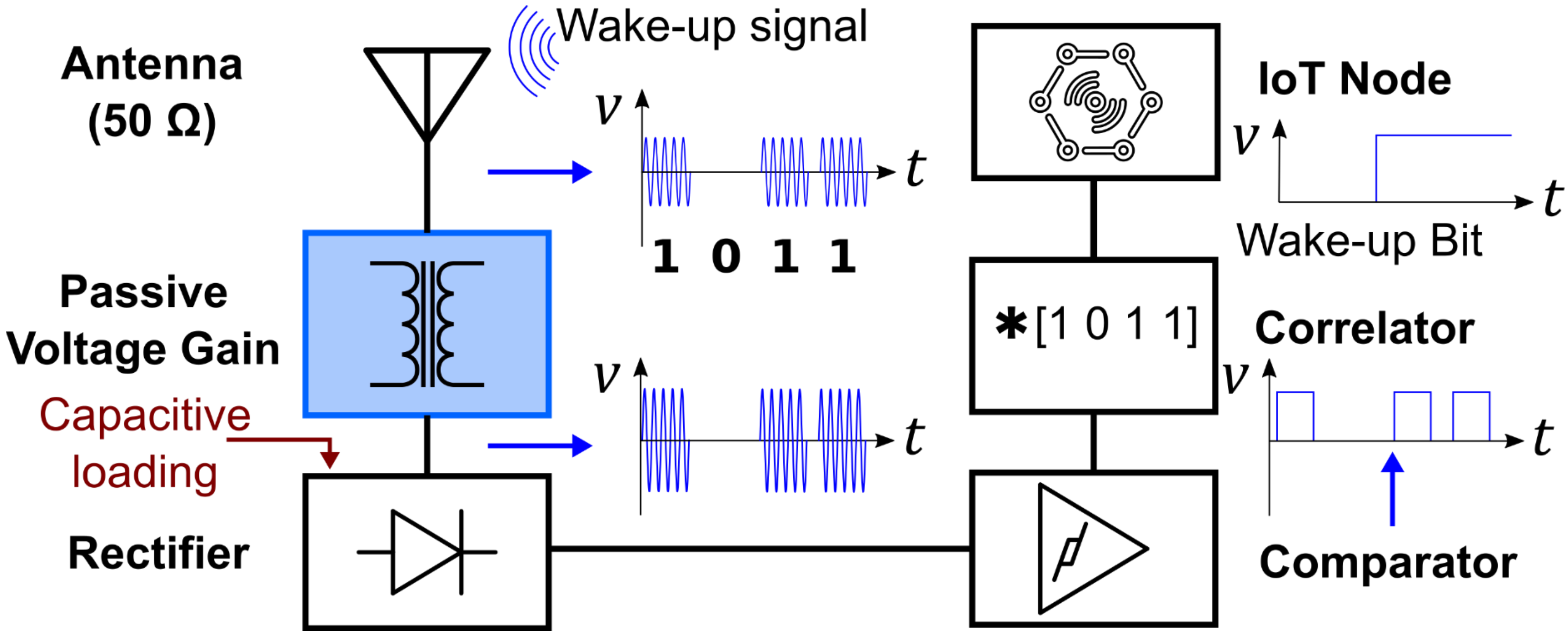


k_t^2=29.5%, Q=527, FoM=160
X-cut, 0° to Z, 4.5 GHz
By S. Gong, et. al. UIUC

Outline

- Motivation and Applications
- Acoustic Signal Processing in LN Thin Films
- Resonator-based Impedance Transformer
- Delay Line-based Chirp Compressor
- Conclusion and Acknowledgement

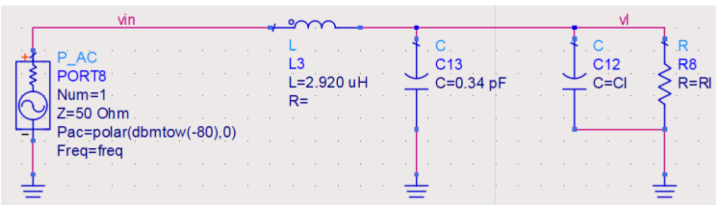
Impedance Transformer for Wakeup

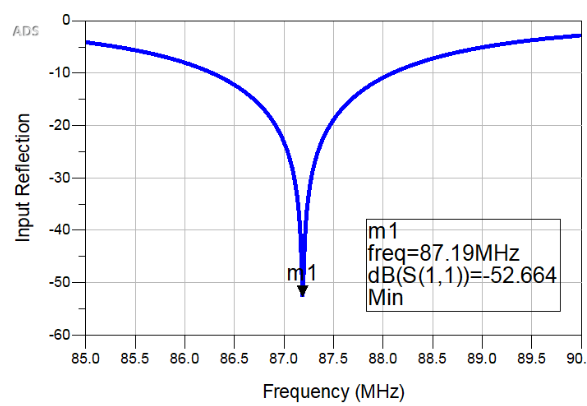


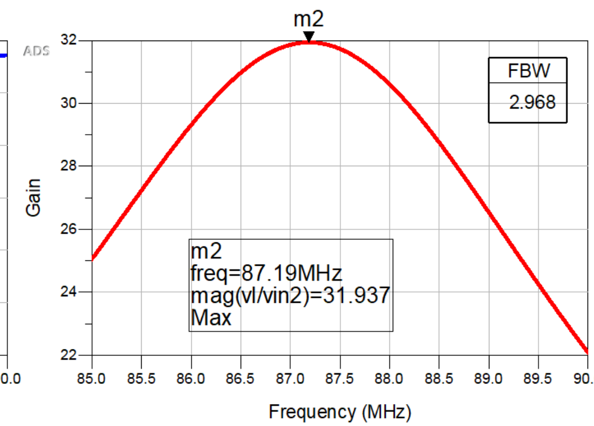
- Require large passive voltage gain to enhance sensitivity
- Require frequency selectivity to reject interference and improve SNR
- Require Integration with CMOS

Resonator as an Inductor

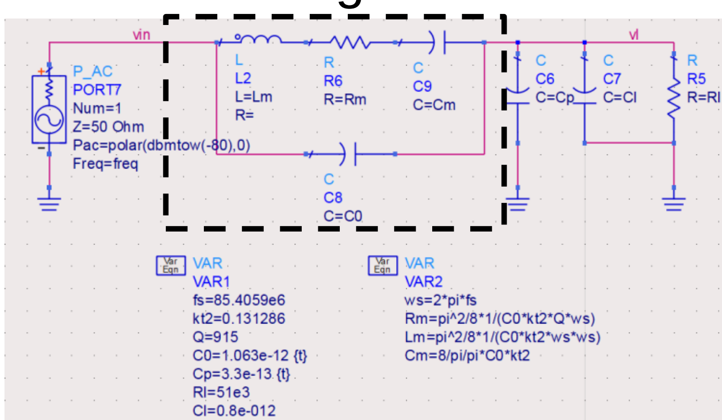
- To conjugate match 50 Ω to the rectifier input of 51kΩ in parallel with 0.8 pF with a lossless ideal LC circuit

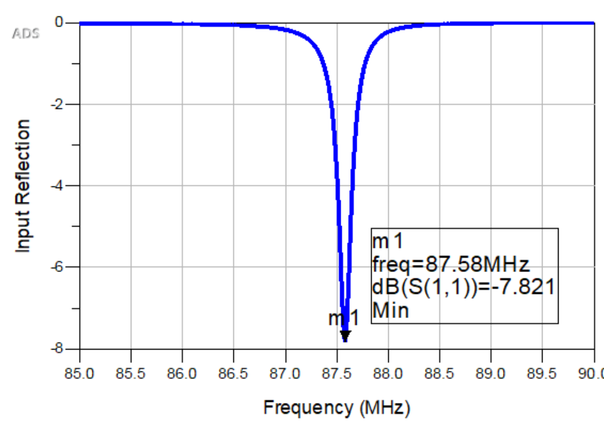


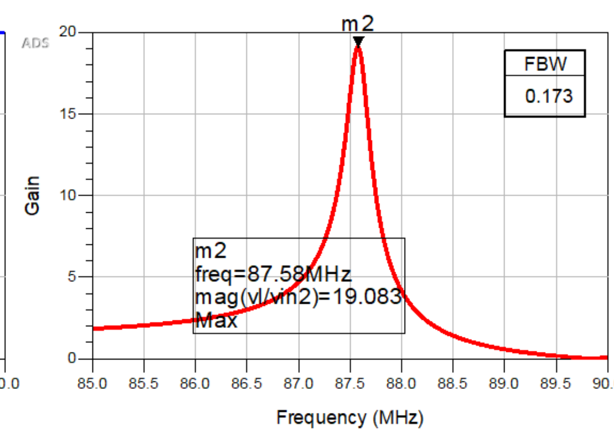




- When using our resonator as the inductor:

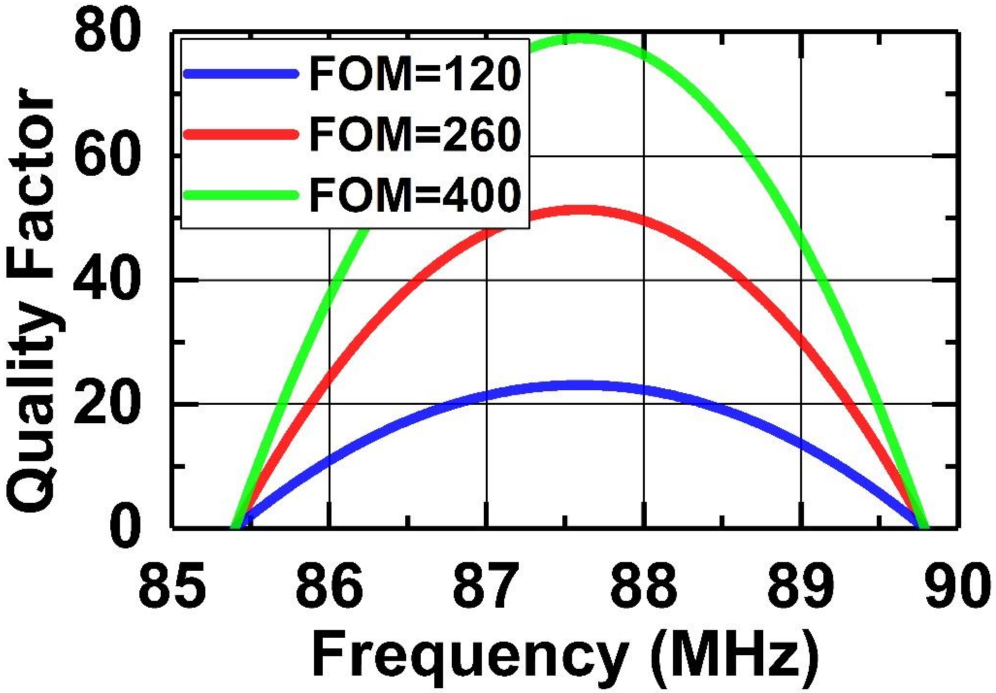




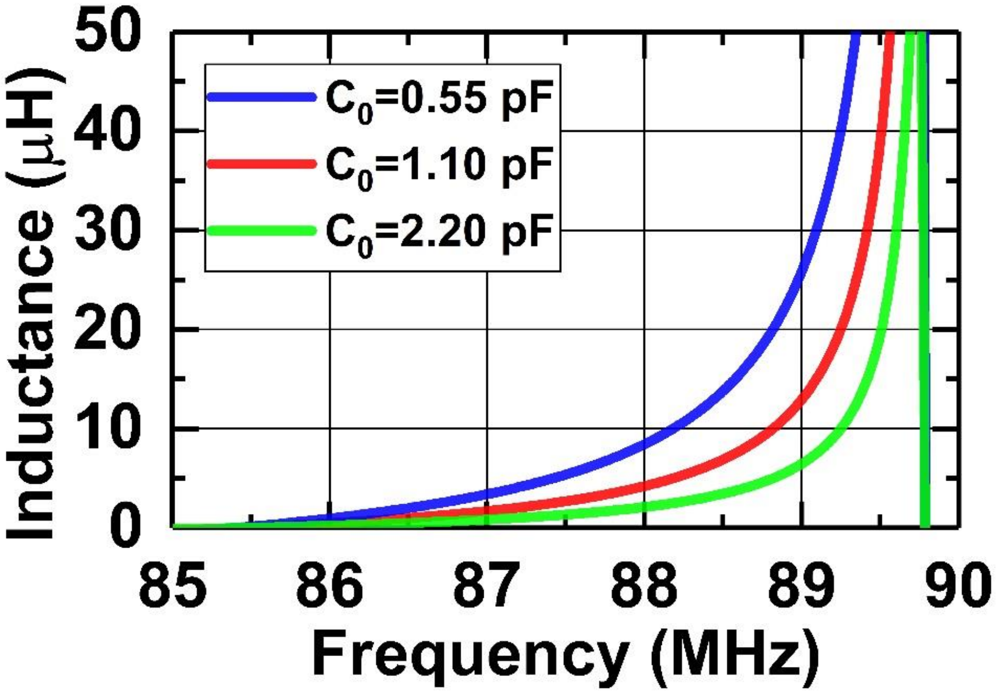


- Treat the shunt capacitor as part of the C_L
- Optimize the components in the dashed rectangle for highest gain

Resonator as an Inductor



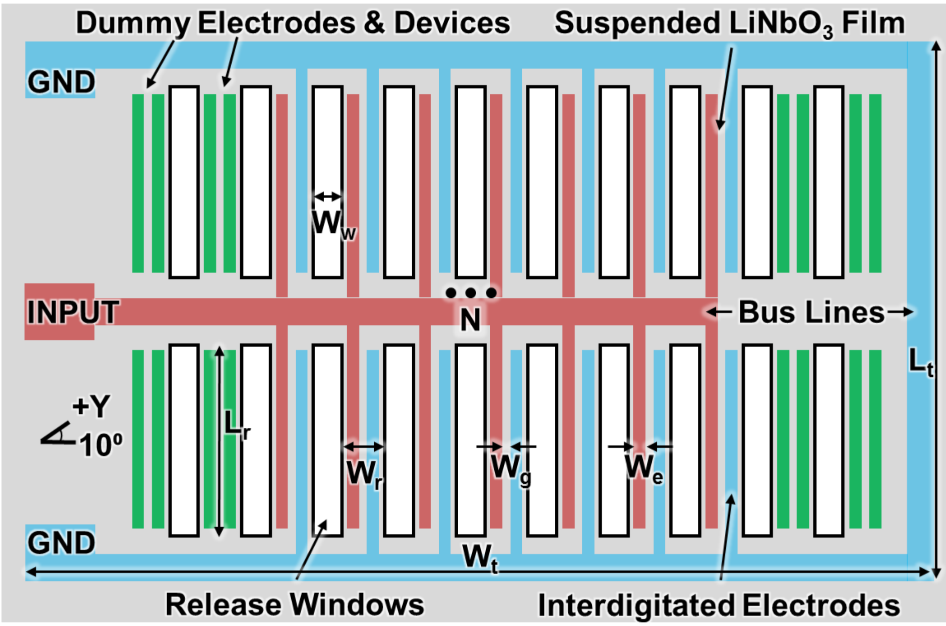
$\text{Max } Q_{ind} \approx 2/\pi^2 \cdot \text{FOM}$



$L \propto 1/C_0$

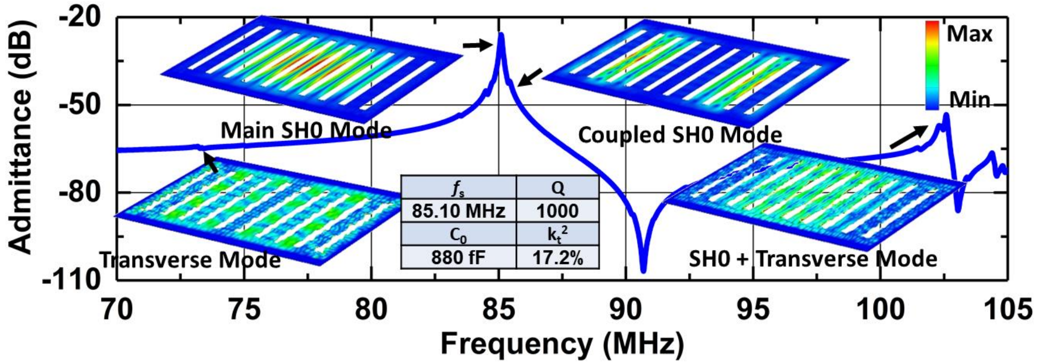
- ✓ Design the resonance such that the system frequency coincides with the frequency with max Q
- ✓ Properly size the resonator for the desired inductance value

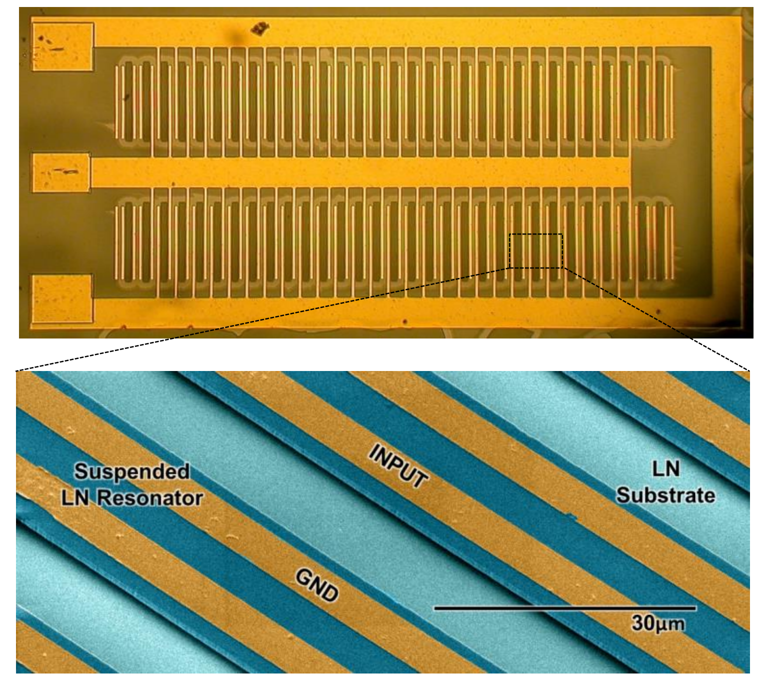
LN Resonator Array



- Array resonators to avoid spurious modes and attain sufficient C_0
- Carefully designed spacing to avoid coupled modes

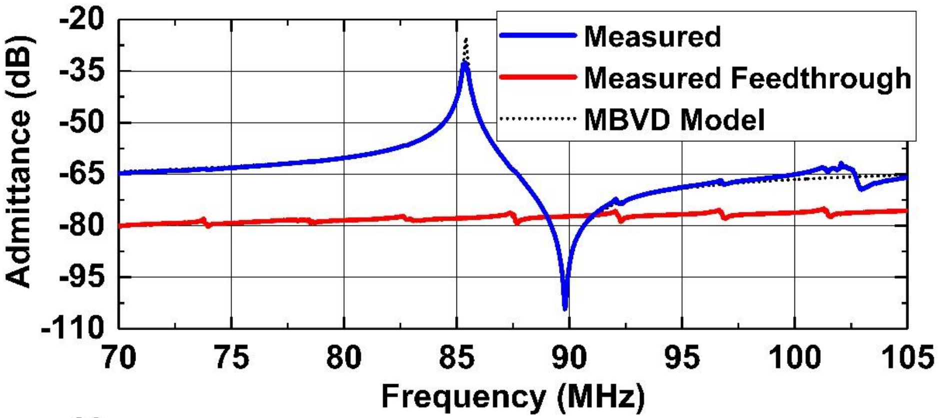
Simulation

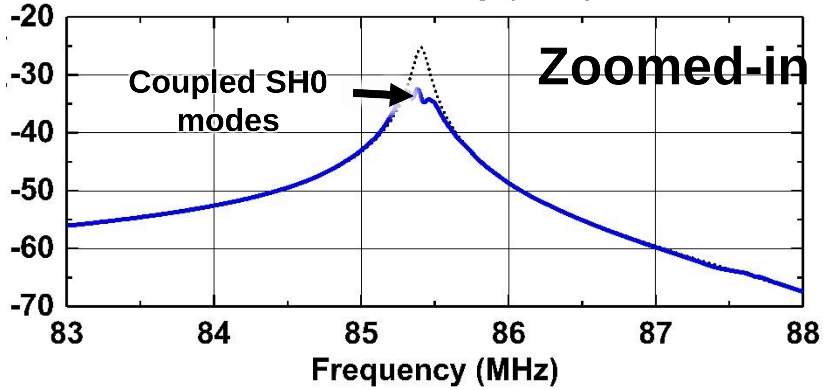




R. Lu, T. Manzaneque, Y. Yang, and S. Gong, “Exploiting Parallelism in Resonators for Large Voltage Gain in Low Power Wake up Radio Front-ends”, in Micro Electro Mechanical Systems (MEMS), IEEE 30th International Conference on, Jan 2018.

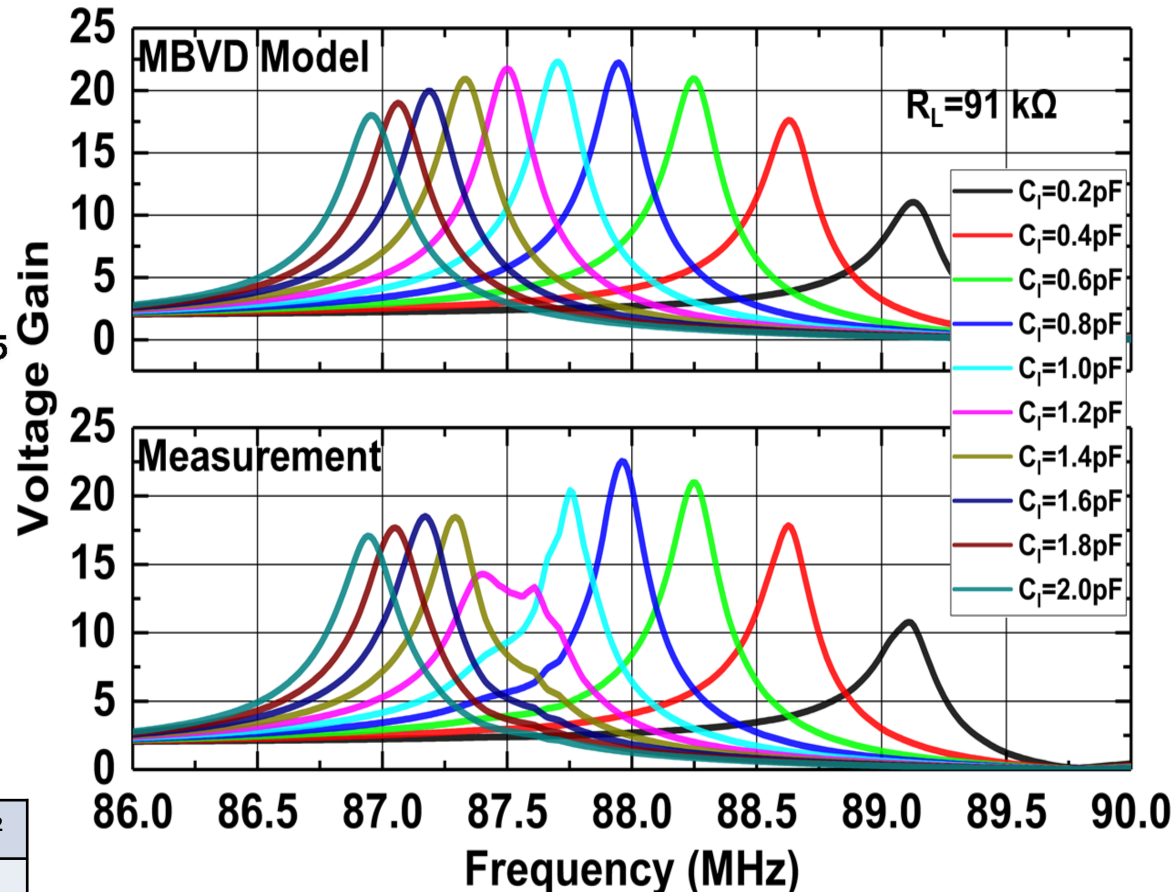
Measured Voltage Gain





f_s	Q	R_m	C_0	k_t^2	$k_{t\_deembed}^2$
85.41 MHz	915	18 Ω	807 fF	13.12%	17.11%
f_p	C_m	L_m	C_f	FOM	$FOM_{deembed}$
89.82 MHz	112 fF	30.99 µH	246 fF	120	157

Voltage gain when connected in series with the rectifier

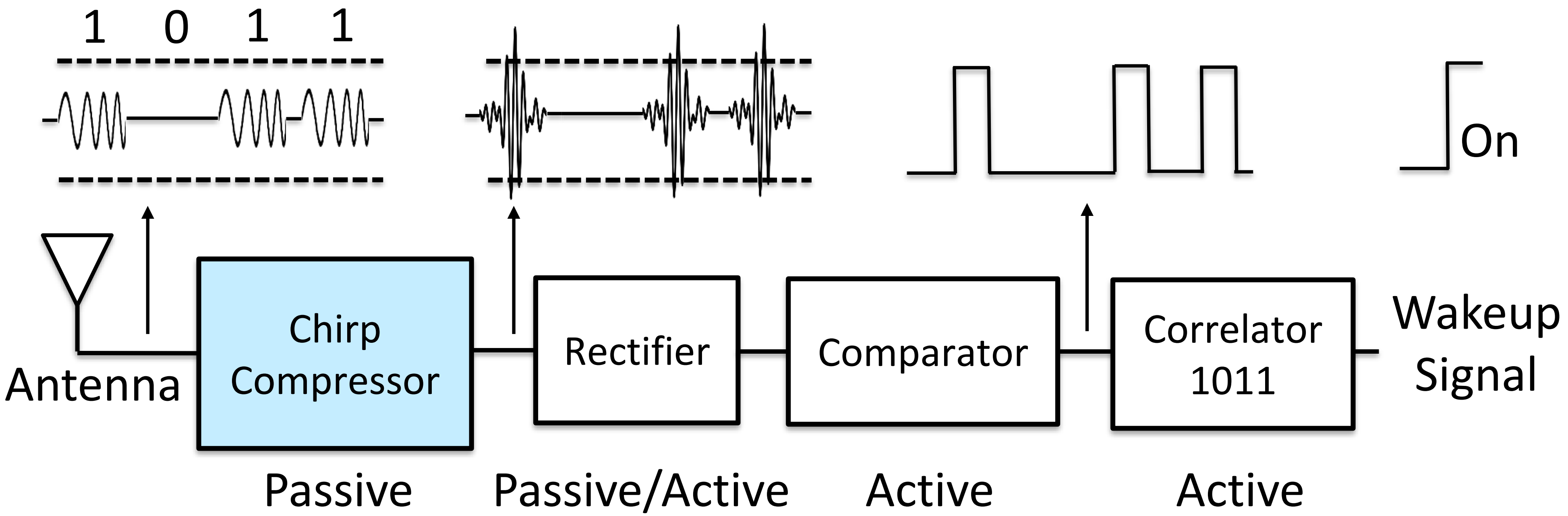


R. Lu, T. Manzaneque, Y. Yang, and S. Gong, "Exploiting Parallelism in Resonators for Large Voltage Gain in Low Power Wake up Radio Front-ends", in Micro Electro Mechanical Systems (MEMS), IEEE 30th International Conference on, Jan 2018.

Outline

- Motivation and Applications
- Acoustic Signal Processing in LN Thin Films
- Resonator-based Impedance Transformer
- Delay Line-based Chirp Compressor
- Conclusion and Acknowledgement

Compression for Wakeup

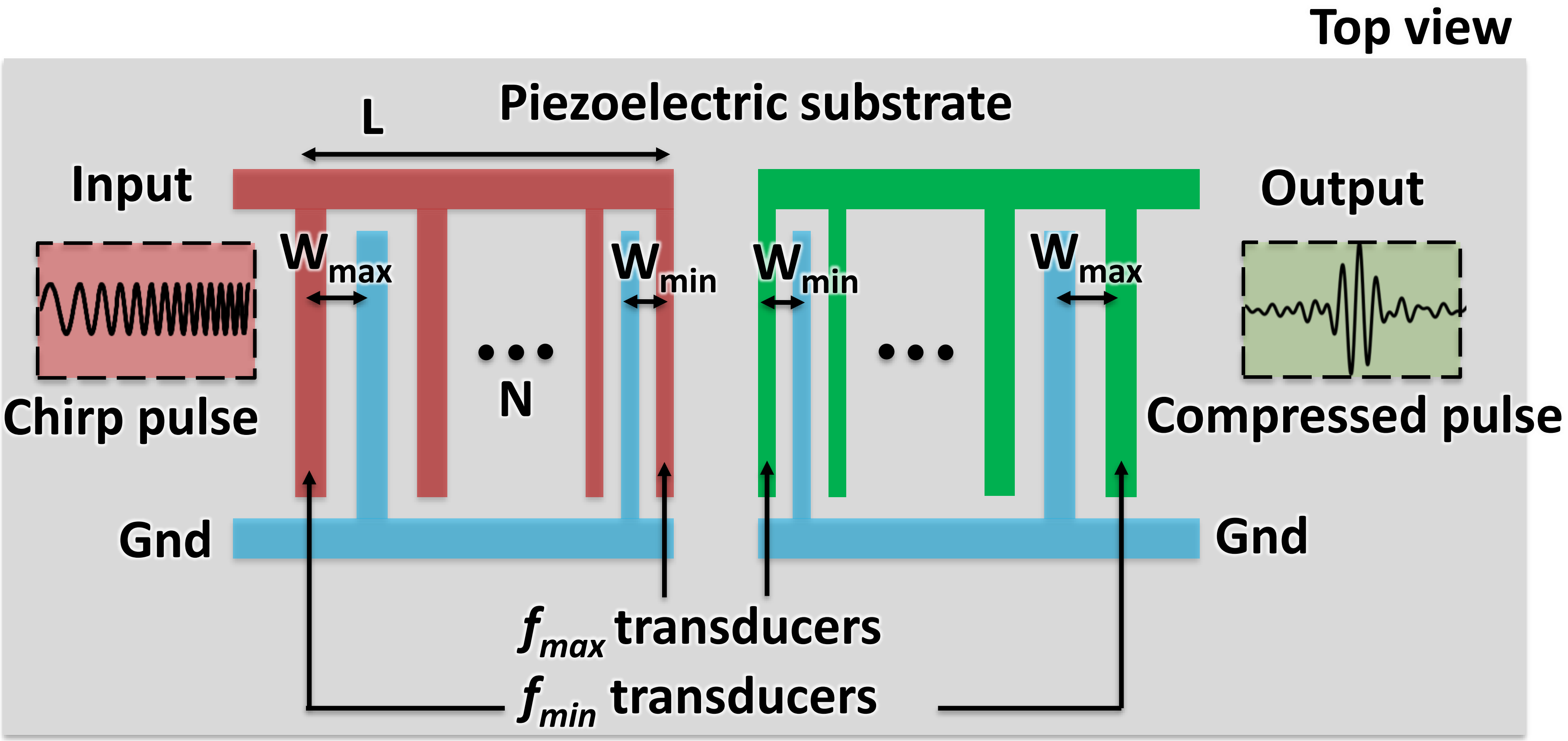


- A compressor provides additional power gain by compressing energy over a period of time to a short pulse
- Input OOF wakeup signal is chirped coded for compression
- Require long delay with low IL over large BW to achieve large processing gain (high SNR enhancement) and net voltage gain
- Gain from compression can be compounded with gain from impedance transformation

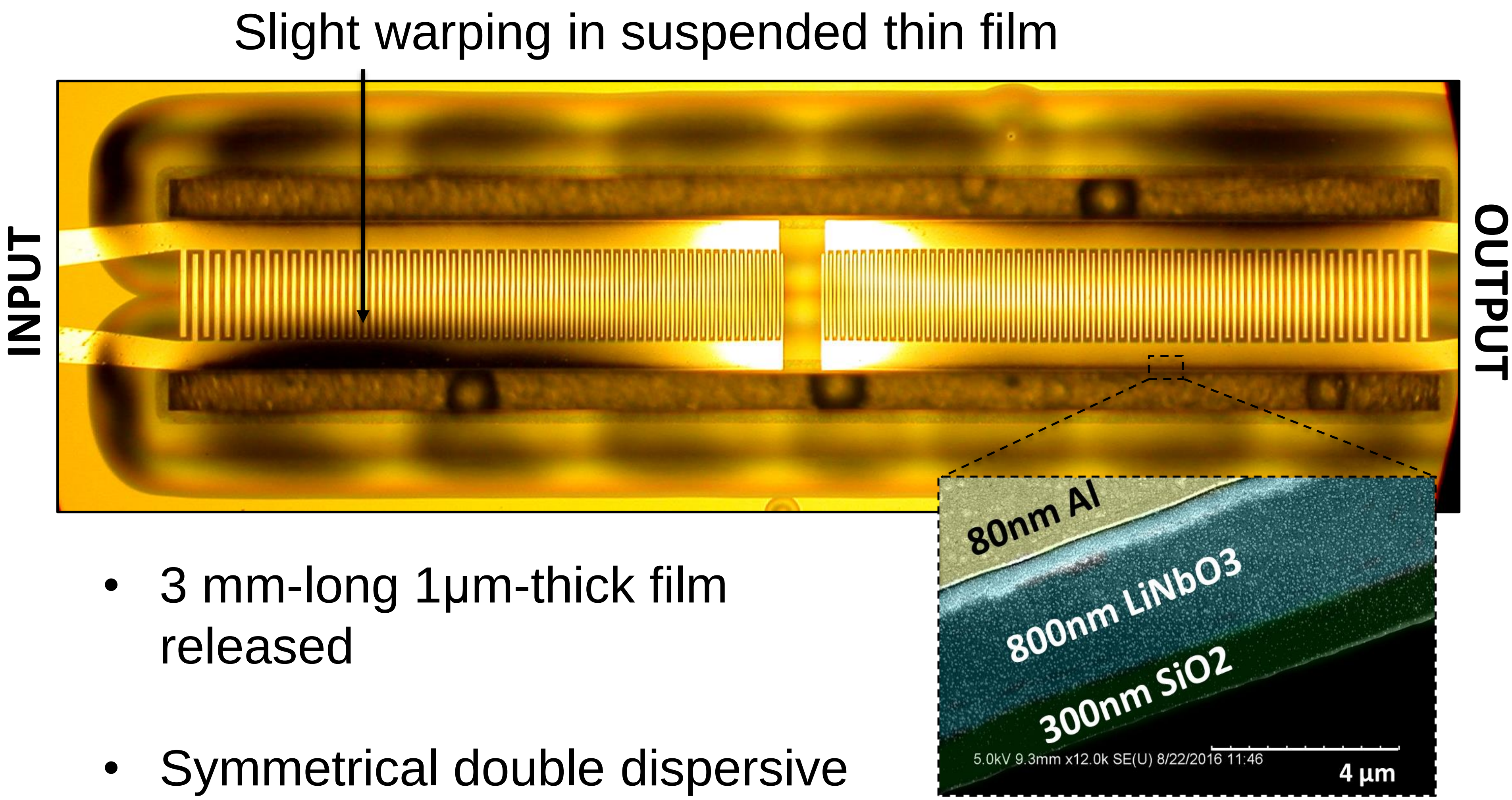
Chirp Compressor Design

Double dispersive delay line formed by two IDTs

- Spatial variation of the electrode pitch ⇒ delay dependent of *f*
- Compression ratio for correlated pulses: *TB*



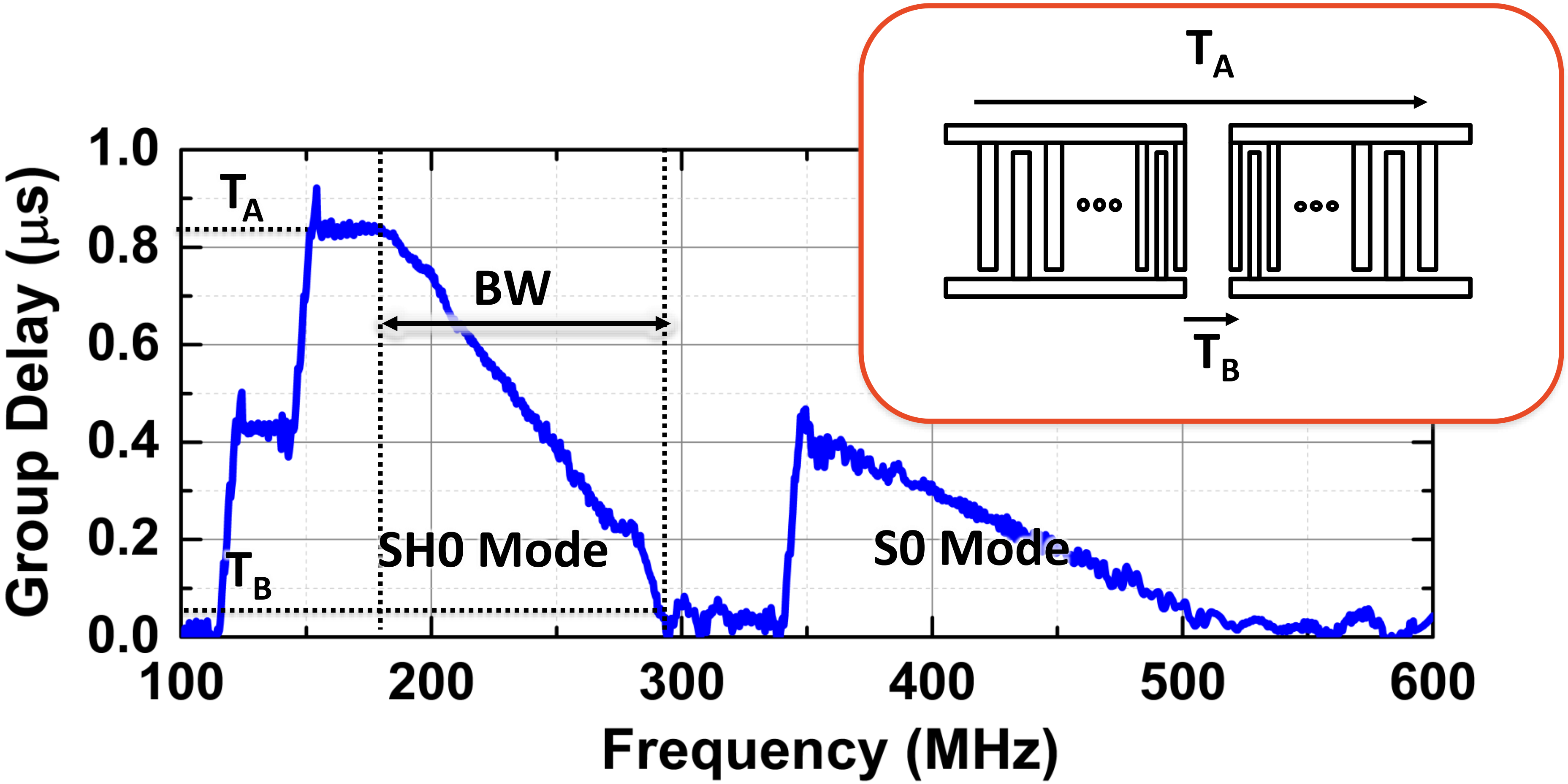
Fabricated Chirp Compressor



- 3 mm-long 1µm-thick film released
- Symmetrical double dispersive

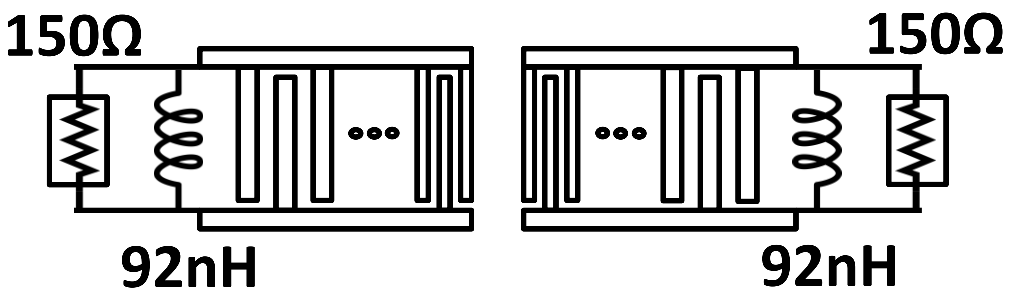
Measured Dispersion

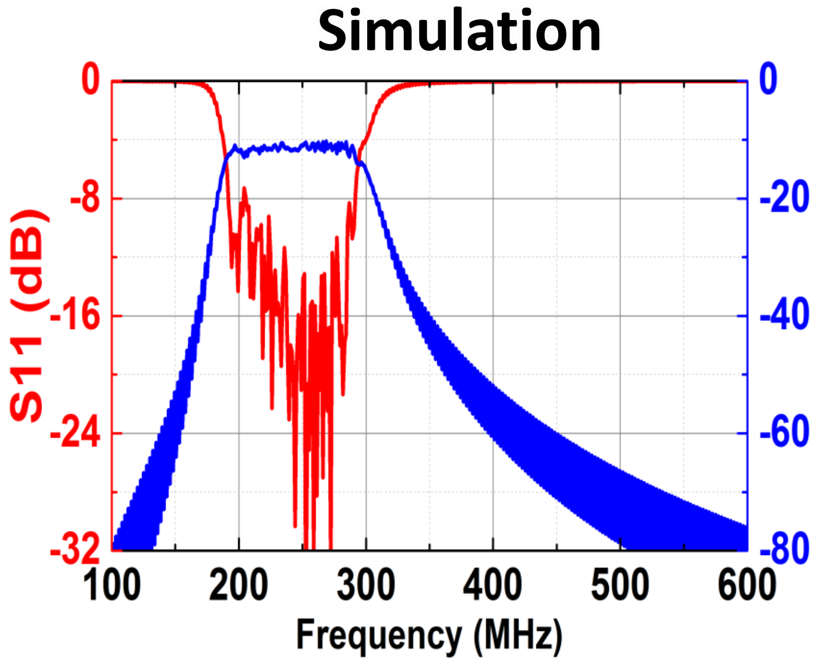
- Group delay $T = 0.8\ \mu s \;\Rightarrow\; v_p = 3750\,\frac{m}{s}$
- Dispersion observed for both SH0 and S0 modes

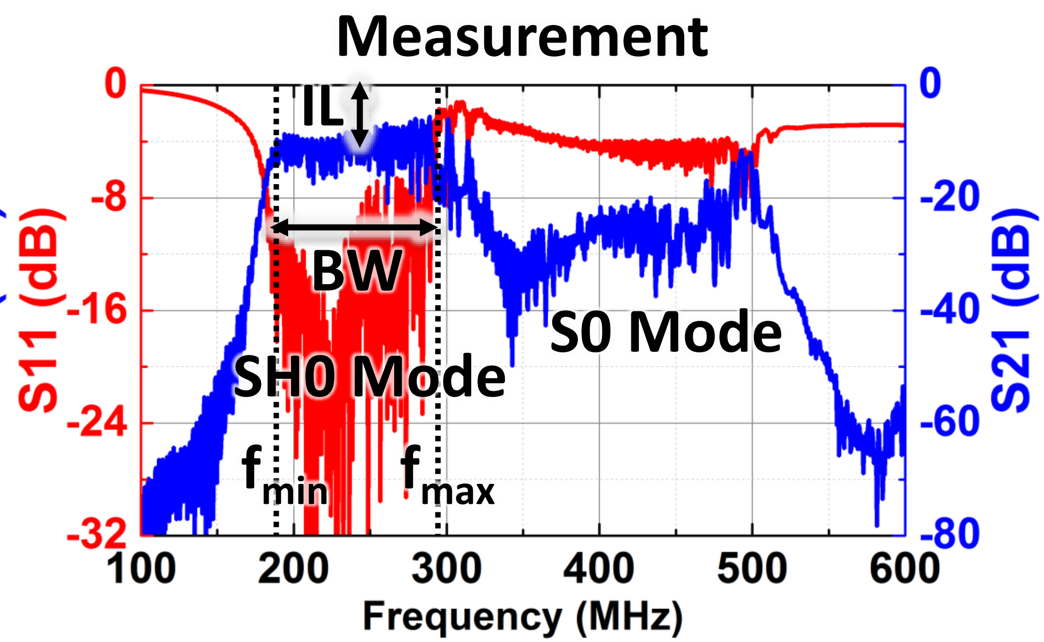


Measured IL

- $f_c = 250$ MHz
- $BW = 125$ MHz
- $IL \approx 10$ dB

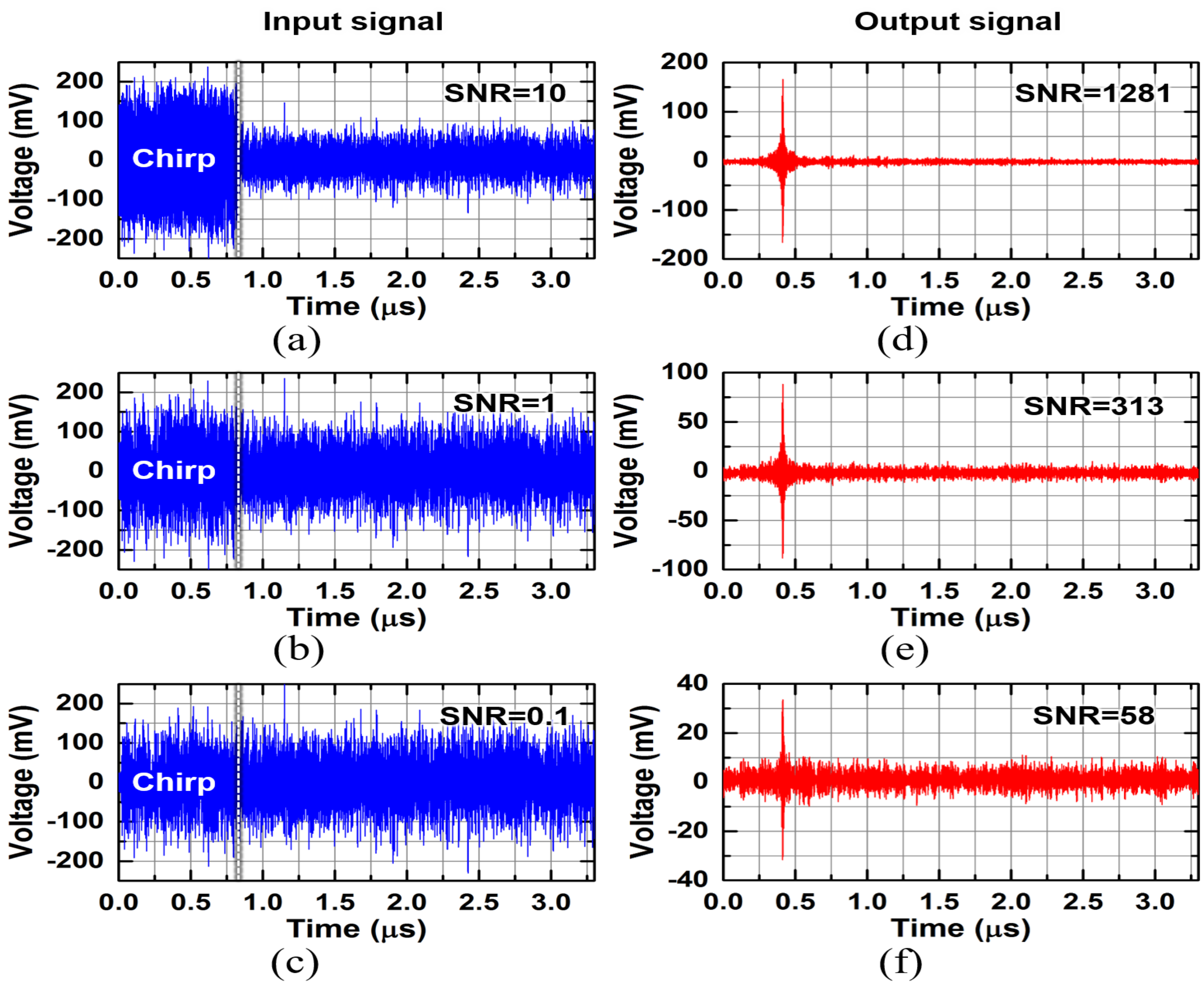






T. Manzaneque, R. Lu, and S. Gong, "An SH0 Lithium Niobate Dispersive Delay Line for Chirp Compression-enabled Low Power Radios" in Micro Electro Mechanical Systems (MEMS), IEEE 29th International Conference on, Jan 2017

SNR Enhancement



T. Manzaneque, R. Lu, Y. Yang and S. Gong, "Lithium Niobate MEMS Chirp Compressors for Near Zero Power Wake-Up Radios," in *Journal of Microelectromechanical Systems*, vol. 26, no. 6, pp. 1204-1215, Dec. 2017.

Acknowledgement

- Funding Support

N-ZERO
SPAR

Thanks Dr. Troy Olsson for valuable feedback!