

# Harmonic Generation to Improve Ultrasound Image Using Piezoelectrical Micromachined Ultrasound Transducers

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## Summary:

Non-linear excitation of Piezoelectrical Micromachined Ultrasound Transducers (PMUTs) produces harmonics generation in sound waves. These harmonics can be used for enhancing image resolution, acousto-optic modulators or multiplexing. In this work we have demonstrated electrical and mechanical non-linear behavior in a PMUT with high frequency resonance and high order harmonics generation.

**Keywords:** PMUT, Ultrasound Image, Non-linearity

## Background, Motivation and Objective

Ultrasound transducers are used for a huge number of techniques, from imaging to communications, chemical and structural analysis. PMUTs have become good candidates for ultrasound transduction for their low-energy consumption, good sensitivities and well-known fabrication techniques. PMUTs are a special case of flexural microelectromechanical systems (MEMS) resonators subjected to non-linear response depending on the excitation.

Under nonlinear response conditions, the spring constant relating the force acting on the PMUT to its vibration amplitude depends on this amplitude through quadratic, cubic and higher-order terms. This amplitude dependence enables the force to act not only at the excitation frequency but also at its harmonics. This nonlinear behavior enables applications such as second-harmonic imaging [1], acousto-optic modulation [2], multiplexing [3], and other multifrequency applications.

For tissue imaging, second harmonic imaging has become of great importance to increase image resolution because of its capacity to reduce artifacts; the energy is concentrated around the main lobe, and the grating lobes and side lobes will have less energy making this less sensitive to off-axis scatters than the fundamental, giving cleaner images [1]. When a single, small PMUT is used, the acoustic energy is radiated in an almost omnidirectional manner, which significantly degrades lateral resolution. In contrast, excitation at higher harmonics results in a more spatially confined radiation pattern.

In addition, it is demonstrated that the combination of higher harmonics (mainly 3rd, 4th and 5th) in a single superharmonic component is a beneficial way to increase the amount of detected energy, preserving the advantages of higher harmonics [4, 5].

Moreover, high-frequency ultrasounds enable the imaging of small-scale features. By exploiting nonlinear effects and applying external pumping, the amplitudes of high-frequency modes can be enhanced.

## PMUTs and measurement set-up

PMUTs have a square shape with an 80  $\mu\text{m}$  side and clamped edges. They are built with a 1.2  $\mu\text{m}$  thick scandium-doped (9.5%) aluminum nitride piezoelectric layer and a 1.5  $\mu\text{m}$  silicon nitride passive layer. The piezoelectric layer is sandwiched between two 0.4  $\mu\text{m}$  aluminum layers, one grounded and the other divided into central and peripheral electrodes to enable differential excitation or detection, with a width ratio of 0.7.

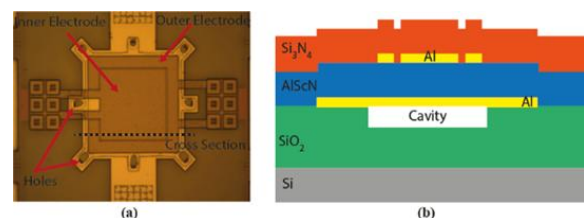


Fig. 1. Optical image (a) and cross section of the PMUT (b)

Fabrication was performed in a commercial CMOS (Silterra) suitable to produce good performance PMUTs for ultrasound purposes [6].

Characterization of the PMUTs non-linearities and measurement of their harmonics were

performed in air, using a home-made interferometer equipped with a He-Ne laser, an avalanche photodiode and a lock-in amplifier.

To characterize the non-linearity, we have driven the PMUT with a relatively high voltage,  $V_{ac} = 26.7$  V peak to peak amplitude, using both electrodes in a differential configuration. PMUT exhibits mechanical (or positive) non-linearity. We can see the characterization in Fig. 2.

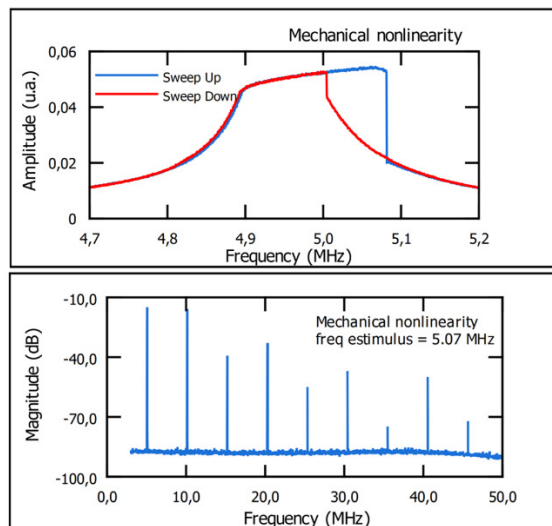


Fig. 2. Optical characterization of PMUT exhibiting mechanical non-linearity (a) and harmonics generation (b)

## Results

To generate the harmonics, we have applied a stimulus of a fixed frequency using the lock-in amplifier as a signal source and we have performed the readout using a spectrum analyser obtaining a comb response (see Fig. 2). The frequency used is the one that allows the maximum vibration of PMUT. We have applied a stimulus with frequency of 5.07 MHz to the PMUT with mechanical non-linearity (just near the high frequency jump) and, as can be seen multiple harmonics appear.

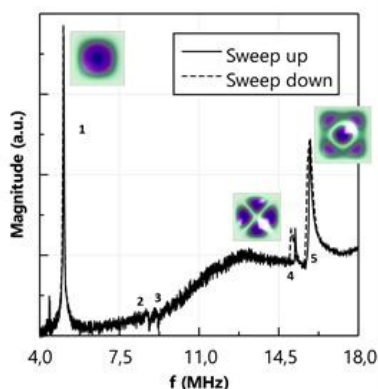


Fig. 3. Excited modes until the fifth. The first, fourth and fifth modes exhibit electrical non-linearities.

We measured the higher-order modes of another PMUT (see Fig. 3) up to the fifth mode, mode (1,3). The results show that nonlinear effects also appear in high-frequency modes (electrical non-linearities in this case). By applying pumping to the fifth mode, its amplitude can be enhanced, primarily using a phase difference of  $30^\circ$  between excitation and pumping (see Fig. 4), at the expense of the amplitude of the first mode.

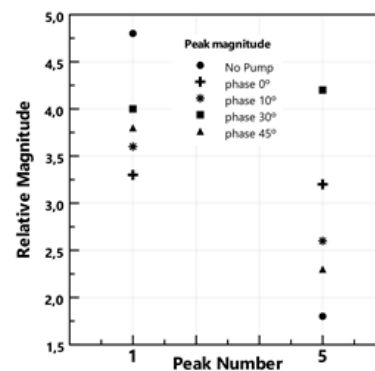


Fig. 4. Pumping of fifth mode of PMUT.

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## References

- [1] A. Bouakaz *et al.*, Native tissue imaging at superharmonic frequencies, transactions on ultrasonics ferroelectrics and frequency control 50, 496-506 (2003); doi: 10.1109/TUFFC.2003.1201462
- [2] G. Pillai *et al.*, Controllable multichannel acousto-optic modulator and frequency synthesizer enabled by nonlinear MEMS resonator, Scientific Reports 11, 10898-1 10898-13 (2021); doi: 10.1038/s41598-021-90248-w
- [3] K. Bhosale *et al.*, Nonlinearity driven higher order harmonics in CMOS-MEMS resonators, IEEE IFCS-ISAF Conference 2020; doi: 10.1109/IFCS-ISAF41089.2020.9234852
- [4] A. Bouakaz *et al.*, Superharmonic imaging: A new imaging technique for improved contrast detection, Ultrasound in Medicine & Biology 28, 59-68 (2002); doi: 10.1016/S0301-5629(01)00460-4
- [5] N.D. Londhe *et al.*, Superharmonic imaging for medical ultrasound: a review, Journal of Medical Systems 40, 279-1 279-16 (2016); doi: 10.1007/s10916-016-0635-x
- [6] I. Zamora *et al.*, Monolithic single PMUT-on-CMOS ultrasound system with +17 dB SNR for imaging applications, IEEE Access 8, 142785-142794 (2020); doi: 10.1109/ACCESS.2020.3013763