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# A novel surface wave transducer based on periodically poled piezoelectric domain

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**Abstract :** A surface wave transducer using a thin ferroelectric film deposited atop silicon and periodically poled has been theoretically analysed. Fundamental guiding properties of such devices are extracted from numerical computations. A low frequency validation of the proposed principle is reported using a periodically poled PZT plate glued on a silicon wafer.

## I. Introduction

The use of InterDigital Transducer (IDT) for the excitation and detection of surface acoustic waves (SAW) has yield an intense industrial and academic research activity since its invention by White and Voltmer in 1965 [1]. Billions of devices have been manufactured based on this principle, starting from simple delay lines, transverse filters, resonators, filters and sensors [2]. The increasing demand for very high frequency devices (1 GHz and above) have pushed the research activity toward new solutions based on thin piezoelectric films on high velocity substrate, silicon for instance [3], but not so much effort was made to find new transducers able to efficiently excite surface waves atop such substrates.

In the proposed work, a new transducer principle still based on piezoelectricity is proposed to excite and detect surface waves atop any kind of substrate. The basic idea consists in generating a periodicity within a piezoelectric layer exhibiting ferroelectric properties (typically PZT, $LiNbO_3$, $LiTaO_3$, $KNbO_3$, etc.) using an appropriate process. Periodically alternated piezoelectric polarisation can be then achieved in such layers by applying an electric field larger than the coercitive field of the layer material (easy in the case of PZT, more difficult in the case of $LiNbO_3$ or other single crystals). This operation requires a conductive layer or substrate below the ferroelectric film. A plane electrode is then simply deposited on its surface. The excitation of an elastic wave guided by the piezoelectric layer is then achieved by applying an alternative signal to the electrodes in regard. Furthermore, the wavelength is equal to the periodicity of the piezoelectric polarisation (the device works on its second harmonic) as shown in fig.1, comparing both principles of standard InterDigital Transducer (IDT) based devices and of the proposed transducers.

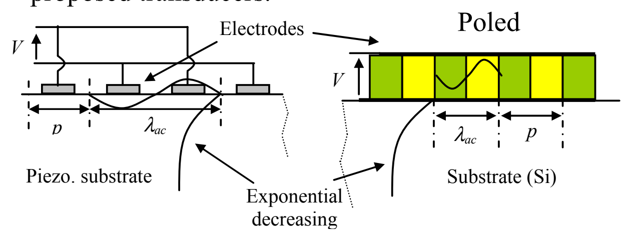


*Fig.1 Comparison between principles of std SAW devices and poled ferroelectric film transducers*

Although such an approach is current in optics, it was not yet efficiently developed for acoustic wave guides. To the best of our knowledge, Triscone & al are the first ones to propose such an approach for acoustics [4]. Other pioneer works are reported in [5]. The proposed paper discusses favourable conditions to excite and detect guided waves using such a transducer. The theoretical analysis is reported together with computation results for typical structures such as PZT on Silicon. The corresponding computations are performed using a mixed periodic finite element analysis/boundary element method enabling a reliable and rapid simulation of inhomogeneous transducers on any stratified media. An experimental validation has been performed at low frequency using a PZT plate glued on a silicon substrate. Experimental results are reported and compared to theory. The fabrication of high frequency devices based on this principle is finally discussed.

## II. Theoretical analysis

In this section, the basic principle of the theoretical analysis of periodic wave guide is very briefly recalled, many related details being already reported in [6]. FEA can be performed for periodic devices with rather simple modifications of the basic algebraic formula relating the displacement and electrical fields to



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the boundary solicitations. First, an harmonic excitation is assumed to be applied to an infinitely periodic structure. The excitation potential $\phi$ is expressed versus the excited cell number $n$ and the coefficient $\gamma \in [0,0.5]$ denoting the excitation phase :

$$\phi_n = \phi_o e^{-j2\pi n\gamma} \quad (1)$$

An harmonic admittance is deduced from eq. (1) by simply dividing the current $I_n$ obtained by summing the nodal chargeon the active electrode by $\phi_n$, the result being independent on $n$ as follows :

$$Y(\gamma,\omega) = I_n / \phi_n \quad (2)$$

$Y$ has to be computed for each $\gamma$ and $\omega$ to fully describe the electrical behavior of the elementary cell of the periodic structure. In the present study, the elementary cell of the periodic array is composed of a ferroelectric film deposited on silicon with two plane electrodes below and atop the piezoelectric layer, as shown in fig.2.

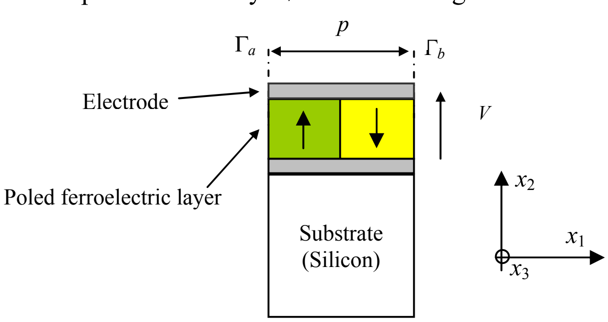



*Fig.2 Definition of the elementary period of the considered poled transducer on Silicon*

The specific boundary conditions applied at the limits $\Gamma_A$ and $\Gamma_B$ of the elementary cell of fig. 2 directly concern the degrees of freedom (dof) at the corresponding boundary :

$$\begin{Bmatrix} u_{\Gamma_B} \\ \phi_{\Gamma_B} \end{Bmatrix} = \begin{Bmatrix} u_{\Gamma_A} \\ \phi_{\Gamma_A} \end{Bmatrix} e^{-j2\pi\gamma} \quad (3)$$

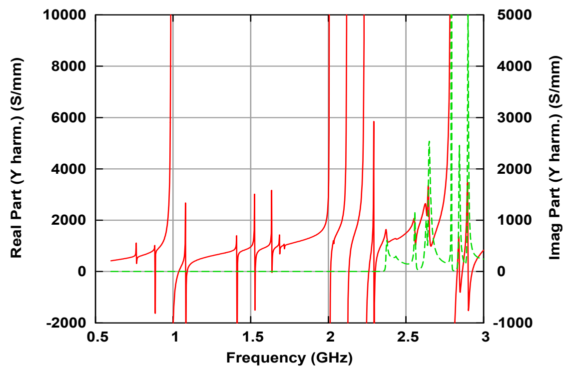
Note that the spatial distribution of nodes (supporting the dof) on $\Gamma_A$ and $\Gamma_B$ must be identical to ensure the coherence of eq. (3). Practically, the case of standard IDT-based devices corresponds to an alternation of electrical potential represented by $\gamma$=0.5 (phase opposition). Here, all the cells are excited in phase, yielding an integer value of $\gamma$(for instance $\gamma$=1). The boundary conditions of eq.(3) are applied in our computation code as a variable change avoiding any re-dimensioning of the FEA system to compute [6]. As above-mentioned, the radiation condition is simulated using a boundary element method, yielding the definition of a ($\gamma$,$\omega$) dependent matrices [6]. Once the final algebraic system solved, for a 1 V. excitation, one simply deduces the harmonic admittance by the following relation :

$$Y(\omega,\gamma) = I(\omega,\gamma) = j\omega \sum_{n=1}^{Ne} Q_n \quad (4)$$

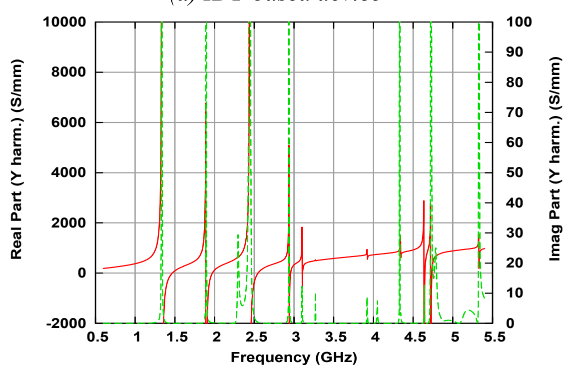
Finally, one can extract different information from the harmonic admittance, such as the wave velocity, reflection coefficient, electromechanical coupling, propagation losses and transducer's directivity (see ref.[7] for the corresponding def.). All the computations are performed using 2nd degree interpolation polynomials for the FEA part of the model and 20 space harmonics (-10 to 9) for the boundary element method, corresponding to stable and reliable calculation conditions. Note that standard 2D finite elements are used since no shear waves are coupled on C-oriented hexagonal materials like PZT.

## III. Numerical computations

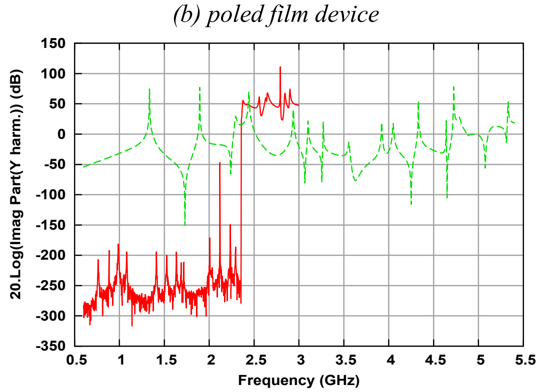
Computation results are now reported for a 0.2µm thick PZT layer deposited atop a (100) silicon wafer, assuming two platinum excitation electrodes of 100 nm thick. The poling is assumed to exhibit a period of 1.2 µm, corresponding to width/thickness of the half period equal to 3. For the sake of comparison, the harmonic admittance of an IDT-based device exhibiting a 1.2 µm period ($\gamma$=0.5) with a metalisation ratio of 0.5 is also computed. Although acoustic and dielectric losses can be considered in our computation, they have been both set to zero in order to specifically point out propagation losses due to bulk radiations. The results are reported in fig.3(a&b). The plotted admittances are normalized for 1 mm aperture. Not surprisingly, the standard IDT-based device response shows many modes, starting at frequency close to 700 MHz. Four well-coupled guided modes are found respectively close to 1GHz and 2.2 GHz. Also a bulk radiation starting at 2.35 GHz is pointed out, corresponding to bulk waves radiated from the surface exhibiting a velocity roughly equal to 5870 m.s-1, which is a quite realistic value for silicon. The situation is substantially different for the case of the periodically poled PZT film excited in phase. Three highly coupled modes are found at 1.35 GHz ($V_m$=2700 m/s, $K_s^2$=17%), 1.9 GHz ($V_m$=3800 m/s, $K_s^2$=27%) and 2.45 ($V_m$=4900 m/s, $K_s^2$=28%) GHz respectively. The most exciting result is that radiation losses also appear at 2.35 GHz but return to zero as soon as 2.5 GHZ and remains negligible until 4.7 GHz (twice more than the previous bulk radiation contribution). A logarithmic plot of the real part of the harmonic admittance shows that a permanent non zero is found for the poled film device, whereas it remains close to zero for the standard device. Nevertheless, one can point out that this non zero real part of the admittance which is due to apart of acoustic energy radiated in the bulk remains very weak in regard with bulk wave radiation for the standard IDT-based device, yielding small losses for the guided waves of the poled device.




*(a) IDT-based device*



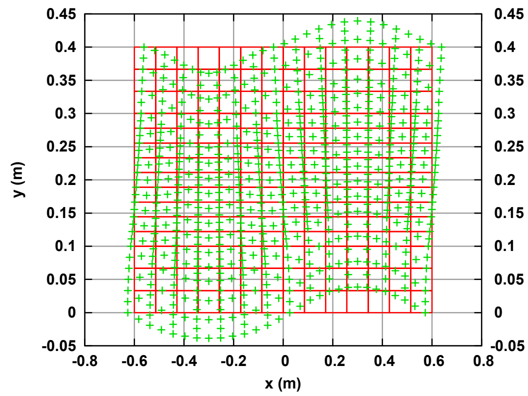

*(b) poled film device*



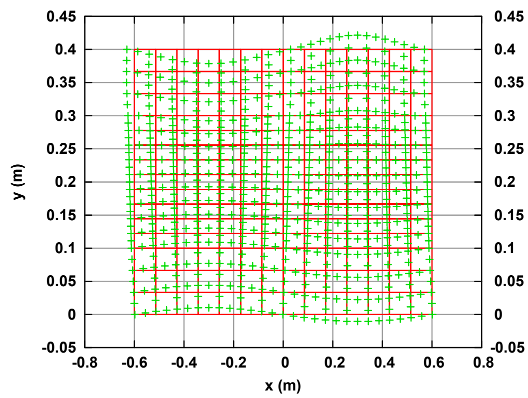

*(c)*

*Fig.3 Comparison between the harmonic admittance of a standard IDT-based device (a) with a poled film transducer (b) and comparison between real part of the harmonic admittance in a logarithmic form (c)*

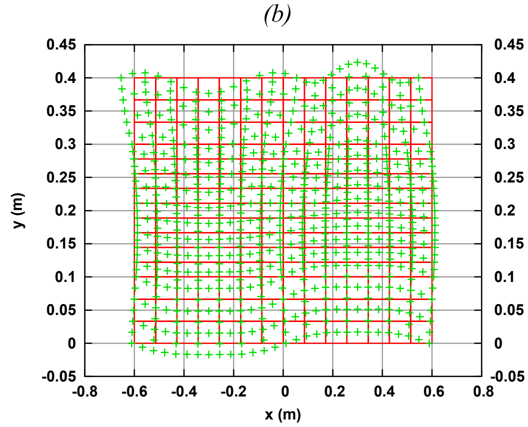
The vibration shape of the 3 first modes are plotted in fig.4. The first mode looks like a 1st order anti symmetric mode, the second a 1st order symmetric mode, and the latter as a anti symmetric exhibiting a complicated surface polarisation.




*(a)*




*(b)*




*(c)*

*Fig.4 Vibration shape of the three first mode guided by the poled film device*
*(a) 1.35 GHz (b) 1.9 GHz (c) 2.45 GHz*

## IV. Experimental validation

A very first experimental validation has been performed at very low frequencies (10-30 MHz range) to validate the transducer's basic principle.

The experiment consists in poling a commercial (Piezo-Ceramics ®) C-oriented PZT plate using a periodic aluminium strip pattern. Since the plate is already poled, one has to determine its poling direction and simply apply a counter poling as shown in fig.5.

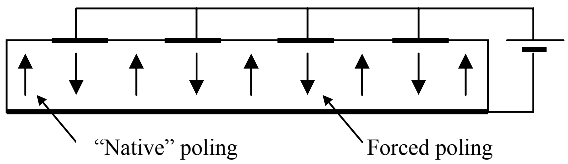



*Fig. 5 Distributed poling in a massive PZT plate*

This operation is performed after gluing the PZT plate on a silicon wafer allowing for the optical detection of the excited mode vibrations. A homogeneous metal overlay is sputtered on the top side of the device to excite and detect the acoustic waves. Figure 6 shows an example of admittance measured for one device. The experimental resonance frequencies are found theoretically within an error of 10%.

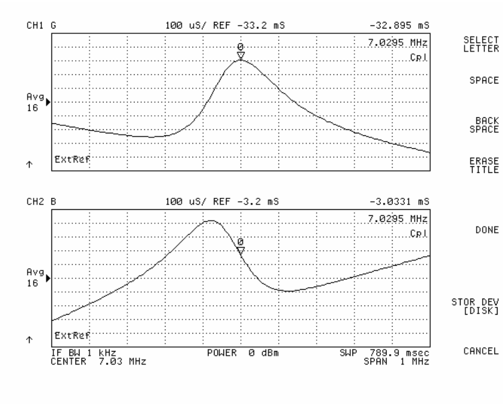
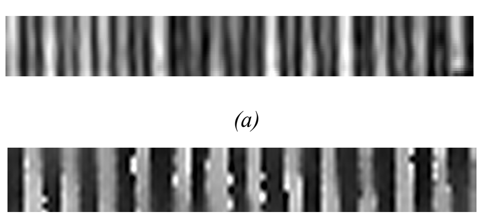



*Figure 6 Example of an experimental admittance of a 200µm period device*

The next figure shows the amplitude and phase image obtained using a laser interferrometric probe (BMI). This figure shows an acoustic vibration exhibiting a wavelength matching well the poling period (200µm)



*(a)*

*(b)*

*Fig. 7 Experimental measurements of vibration shapes using an interferrometric laser probe (a) amplitude (b) phase*

## V. Conclusions

A new transducer principle based on alternated poling domains in a ferrolectric thin film atop a silicon substrate has been analysed theoretically, pointing out very attractive properties significantly different from standard SAW devices. Numerical computations have shown that well coupled waves can be excited with a gain in operating frequency due to the fact that the wavelength matches the period of the structure. Also it has been shown that waves above the frequency cutoff corresponding to the substrate SSBW can be guided contrarily to SAW devices. A first experimental device operating at low frequencies has been fabricated and successfully tested. More work will be now devoted to the demonstration of this new principle at frequencies above 1 GHz, to try and defined the actual limit of devices operating on that mode.

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