New Radio-Frequency resonators based on Periodically Poled Lithium Niobate thin film and ridge structures

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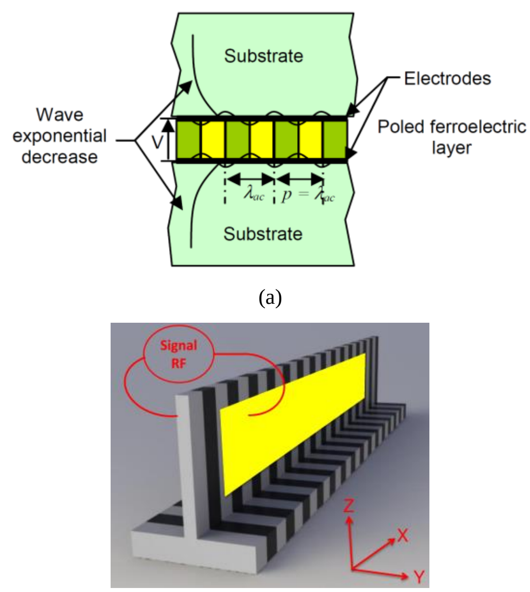
***Abstract*— In this paper, we present new results on the development of an original acoustic waveguides concept based on a Periodically Poled Lithium Niobate transducer. Periodically poled transducers have been investigated recently as an alternative to classical inter-digital transducers for the excitation and detection of guided acoustic waves. We expose here two different structures of RF resonators based on this concept: a "Silicon/Gold layer/PPLN thin film/Gold layer/Silicon" stack and a PPLN-ridge structure. Simulations, fabrication and experimental results of both resonators are presented. "Si/10 µm-thick PPLN/Si" and "PPLN-ridge (11 µm-wide and 250 µm-deep)" resonators with a poling period of 50 µm have been achieved. The experimental admittances of these devices have pointed out the existence of an isolated mode operating at frequencies near 110 MHz for the stack structure and near 160 MHz with an electromechanical coupling of about 19 % for the ridge structure. These results are in agreement with the finite and boundary elements simulations.**

Keywords - resonators; acousto-electric wave; periodically poled lithium niobate; wafer bonding; ridge; single crystal thin film; electromechanical coupling

I. Introduction

New guiding principles are currently investigated to develop high frequency devices capable to answer the RF manufacturer demand for telecommunication components. Nowadays, these components are more and more based on acousto-electric devices due to an easy miniaturization and the use of low cost materials such as surface or bulk acoustic waves components. We suggest here two different structures based on a new acousto-electric concept: a Periodically Poled Lithium Niobate (PPLN) transducer has been investigated as an alternative to classical inter-digited transducers for the excitation of guided acoustic waves [1]. The first compact structure based on a "Silicon/Gold layer/PPLN thin film/Gold layer/Silicon" stack (Fig. 1a) enables to guide without losses an acoustic wave operating at high frequency with a simplified package [2]. One RF application of this structure could be an ultra-stable oscillator. The second one, a PPLN-ridge structure (Fig. 1b), allows the excitation of an acousto-electric wave at high frequency with an electromechanical coupling (k^2) better than 20 % [3]. One RF application of this second structure could be a wideband filter.

In this work, we present the concept, the fabrication process and the experimental results of both new acoustic resonators (PPLN-stack and PPLN-ridge). The PPLN-stack structure is based on the double gold bonding at room temperature of the PPLN wafer onto silicon plates. The PPLN wafer is then thinned at a few microns by lapping and polishing techniques. The PPLN-ridge structure is achieved by dicing a ridge in a poled plate with a diamond-tipped saw and plating the ridge walls to define the electrodes. These new devices have been modeled with our finite and boundary elements simulation tool to determine the most interesting design.



(b)

Fig. 1. Scheme of the RF resonators structures, (a) "Si/PPLN layer/Si" stack and (b) PPLN-ridge structure.

II. PPLN THIN FILM RESONATOR

In this part, the Periodically Poled Lithium Niobate waveguide is presented. The concept and some simulations of the PPLN thin film resonator will show the interests of this structure. The fabrication flowchart of this resonator and radio-frequency characterizations of a test vehicle will be presented.

A. Concept and simulations [2]

An innovative solution has been retained in order to answer to the need of high frequencies sources (RF until X band domain). These sources indeed need spectral purity, short-term stability and phase noise around the carrier wave. The purpose is to fabricate resonators based on the acousto-electric waves propagation through a waveguide. This resonator operates with a Periodically Poled Transducer (PPT) structure inserted between two guiding substrates. A wave propagates without any acoustic losses and decreases exponentially in the structure (fig. 1a). Silicon wafers have been chosen as guiding materials because silicon is low-cost and well-suited in microelectronic systems. Compared to Inter-Digital Transducers (IDT), this PPLN waveguide transducer is more robust (no short-circuit between electrodes), a held in power better (massive electrodes) and a frequency twice higher for a same period.

The simulations of the waveguide structure are based on our finite and boundary element (FEM-BEM) simulation tool. Figure 2 shows the harmonic admittances obtained for various thicknesses of PPLN transducer (50µm-period) bonded between two silicon substrates.

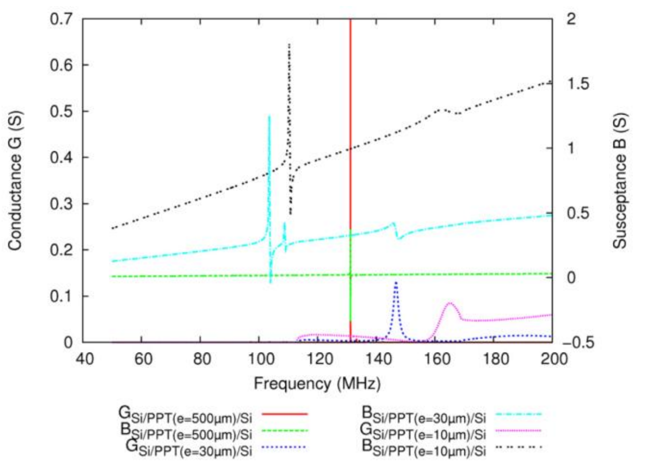


Fig. 2. Harmonic admittances of a Si/PPLN transducer (50µm-period)/Si waveguide for different PPLN transducer thicknesses (e = 500, 30 and 10µm).

We can note that when the PPLN transducer (PPT) thickness is reduced, a new acoustic wave is guided by the structure. For a 10 µm-thick PPLN transducer, this wave is isolated with a pure spectral signal. Figure 3 shows the analysis of dispersion properties of this wave for a 50µm-period PPLN transducer.

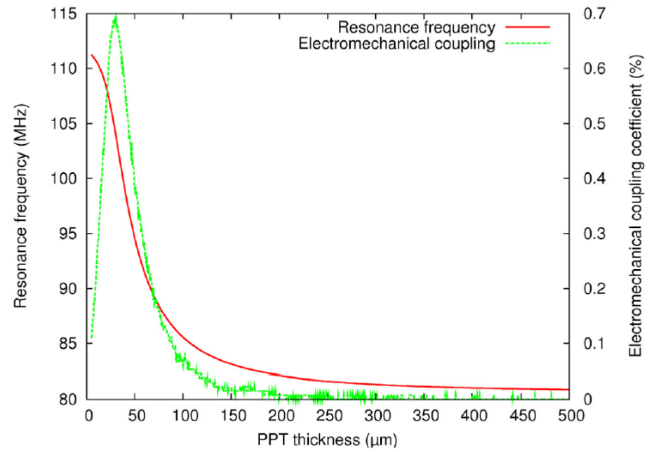


Fig. 3. Evolution of the isolated mode synchronism frequency and electromechanical coupling for PPLN transducer thicknesse ranging from 1 to 500 µm for a 50µm-period PPT.

We can see an optimum point with a maximum electromechanical coupling (k^2 = 0.7%) for a 30 µm-thick PPLN transducer.

B. Fabrication and RF characterizations [4]

The dispersion properties analyses of a device composed of a Si/PPLN transducer/Si combination have shown a favourable operating point for which a single wave is excited with a maximum electromechanical coupling (about 1%). This point is obtained for a thickness/period ratio of about 0.6 corresponding to a 30 µm-thick PPT for a 50 µm-period. Thus, the PPT must be thinned before the second bonding as illustrated in Figure 4.

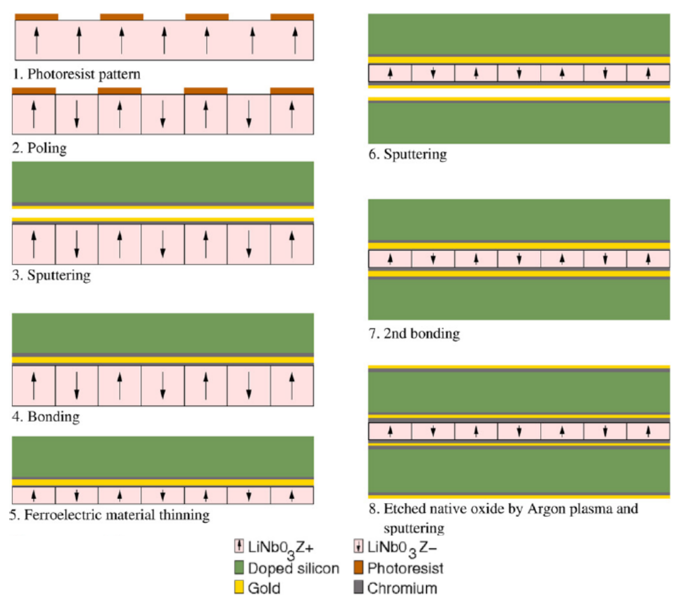


Fig. 4. Flowchart of the Si/thinned-PPLN transducer/Si resonator fabrication.

In order to obtain a single-crystal PPLN thin film bonded between two silicon wafers, we have developed a technology based on a metal diffusion bonding and a chemicalmechanical thinning. First of all, a dedicated poling bench by electric field application allows to invert the ferroelectric domains of 500 µm-thick Z-cut lithium niobate wafer. A Chromium/gold layer is then deposited on the silicon and the PPLN wafers and they are put into contact in a wafer-bonder equipment. The bonding is achieved at room-temperature by applying a strong pressure. The next step is the thinning of the PPLN wafer by lapping and polishing techniques. Hybrid wafers are then achieved on 3 and 4 inch wafers, the bonded surface is more than ninety-eight percent, the surface roughness less than 1 nm, the thickness layer variation is less than 1 µm and the minimum thickness layer achieved is equal to 1 µm. Finally, the "Si/thinned PPLN" stack is bonded again on a silicon wafer in order to form the "Si/thinned PPLN/Si" structure.

"Doped Si/thinned PPLN transducer/Doped Si" resonators have been successfully fabricated on a PPLN exhibiting a poling period of 50 µm (Fig. 5).

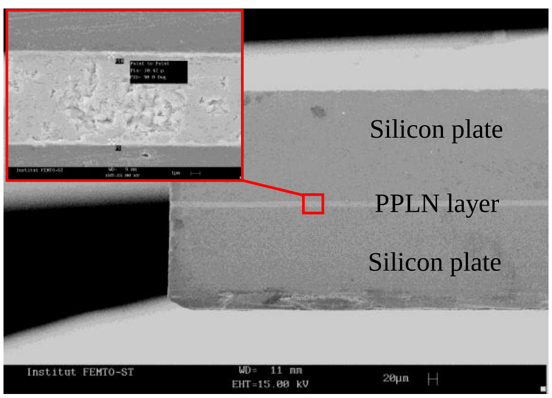


Fig. 5. SEM views of the "Si/PPLN layer/Si" stack.

"Doped Si/Au/10µm-thick PPLN/Au/Doped Si" test vehicles have pointed out the existence of an isolated mode operating at frequencies near 110 MHz (Fig. 6).

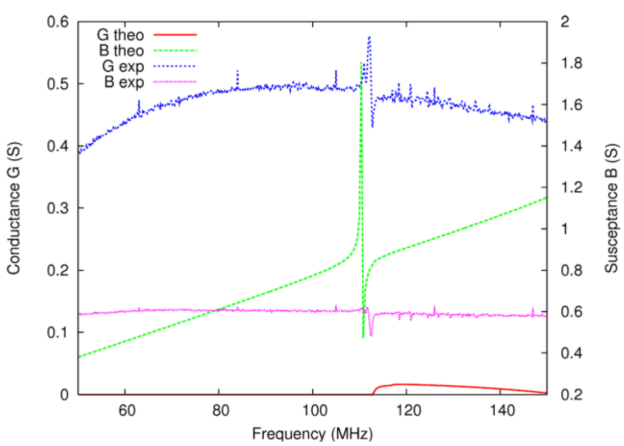


Fig. 6. Theory/Experiment results of the "Si/PPLN layer (50 µm-period, 10 µm-thick)/Si" resonator.

Acoustic response presents some parasitic effects due to the geometry quality but the results are encouraging with a good theory/experiment agreement.

III. PPLN RIDGE RESONATOR

In this part, the Periodically Poled Lithium Niobate ridge is presented. The concept and some simulations of the PPLN ridge resonator will show the interests of this structure. The fabrication flowchart of this resonator and radio-frequency characterizations of a test vehicle will be presented.

A. Concept and simulations [3]

According to PPT principles, the new transducer is based on a periodically poled material. As shown previously the Z+/Z- polarity alternation allows for constructive interference when exciting the structure using electrodes deposited on top and bottom sides of the plate. However, such a structure does not allow for reaching coupling factors larger than 1%, which is far to comply with RF filter requirements. The leading idea of the new concept consists in testing a new configuration in which the excitation is achieved on the (YX) surface instead of (ZX) as presented on the figure 1b.

The simulations of the PPLN ridge structure are based on our finite and boundary element (FEM-BEM) simulation tool. Two main contributions are excited in the PPLN ridge structure: a longitudinal mode and a shear mode. Figure 7 shows the dispersion analysis of the both modes and their electromechanical coupling.

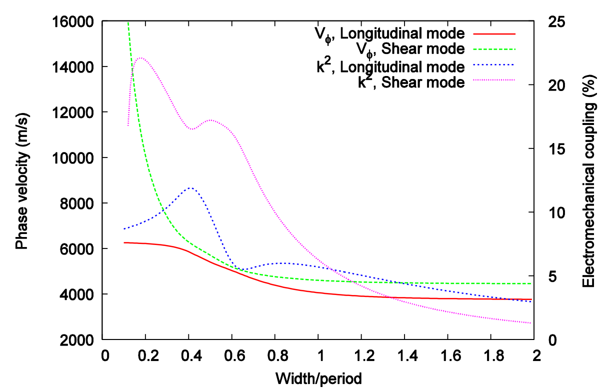


Fig. 7. Phase velocity and electromechanical coupling versus width/period ratio for the longitudinal mode and shear mod of a PPLN ridge transducer.

The electromechanical coupling and the phase velocity of both modes depends on width/period ratio. The figure 7 allows for determining of the optimal ratio for promoting the coupling factor. Best electromechanical couplings are reached at w/λ ratios of 0.4 (k^2=12%) and 0.2 (k^2=22%) for longitudinal and shear modes, respectively. Another advantage of this configuration is the high equivalent phase velocities of these modes. Phase velocities can reach 6500 $m.s^{-1}$ and 18000 $m.s^{-1}$ for longitudinal and shear modes respectively.

B. Fabrication and RF characterizations [3]

In order to fabricate the PPLN ridge structure (Fig. 1b), the fabrication process is divided in to six main steps (Fig. 8). The first one is the periodic inversion of a 500 µm-thick Z-cut lithium niobate wafer (Fig. 8a and b) by electrical field application [1]. After the poling step, the wafer is coated with a photoresist overlay and diced to fabricate ridge shaped transducer. Saw cuts are manufactured along X axis over depths of 10 µm up to 400 µm (Fig. 8c and d). Aluminum electrodes are then sputtered on the device walls and patterned by lift-off (Fig. 8e and f).

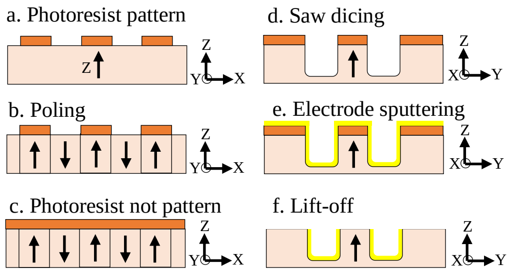


Fig. 8. Flowchart of the PPLN ridge resonator fabrication.

Dicing step is the main technological process for this kind of PPLN-ridge resonator, it also provides the final structure of the device and therefore conditions the transducer performance which largely depends on dicing quality and precision. This process is achieved using a Disco saw, with diamond blade of 400 µm width and 5.2 cm diameter. Two ridge width spaced cuts are achieved to obtain one ridge. Parameters like feed rate and operating speed have been determined to get the best side surface quality. The dicing method consists of dicing a ridge to a depth under wafer thickness (500 µm), allowing narrower ridge than 10 µm and higher than 100 µm. Ridge width can be lower than 10 µm for a depth higher than 100 µm. This method allows very narrow ridges then yielding high working frequencies (above one GHz) and w/λ ratios of 0.2 and 0.4. An example of these ridges is shown on figure 9.

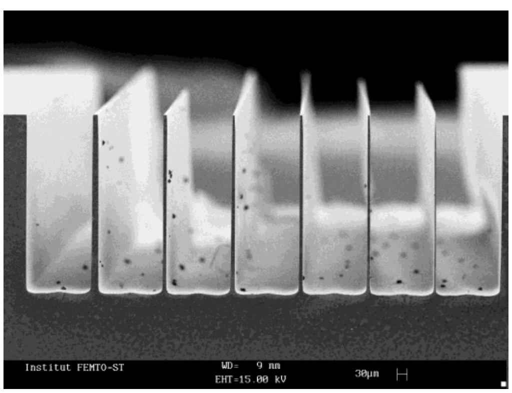


Fig. 9. SEM view of PPLN ridges of 250 µm-deep for different width (20 µm up to 3 µm).

A PPLN ridge resonator have been fabricated in order to operate near the 0.2 w/λ ratio. A lithium niobate wafer has been poled with a 50 µm-period. A ridge waveguide has been diced in this PPLN network with 11 µm-wide and 250 µm-deep. The radio-frequency characterization of this PPLN ridge resonator is presented on the figure 10. A good agreement between theoretical and experimental results of the two investigated modes at 120 MHz and 160 MHz respectively is noted. The measured electromechanical coupling of the shear mode is better than 19 %.

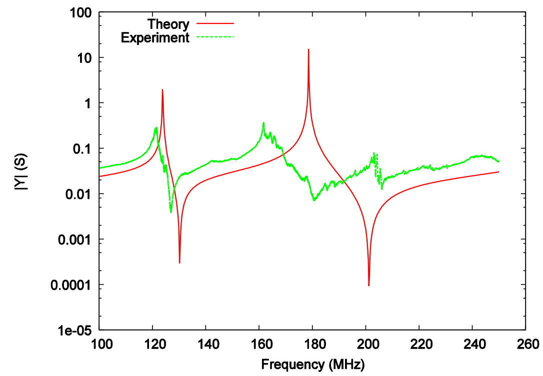


Fig. 10. Theory/Experiment admittances of the PPLN ridge resonator (50 µm-period, 11 µm-wide and 250 µm-deep).

IV. Conclusion

Two radio-frequency structures using PPLN to excite acousto-electric waves have been successfully manufactured to allow for experimental investigation of waves excited and propagating in thin film PPLN and PPLN ridge. The obtained results are encouraging, emphasizing a very good agreement between simulation and experiment. The "sandwich" resonator is auto-encapsulated and the guided monomode is insensible to the environment. This structure is well adapted to answer to the need of high frequencies sources. The ridge resonator presents interesting properties as the high velocity and the high electromechanical coupling of the waves. This structure is well adapted to answer to the need of wideband filter in the telecommunications domain.

Acknowledgment

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References

[1] E. Courjon, N. Courjal, W. Daniau, G. Lengaigne, L. Gauthier-Manuel, S. Ballandras, and J. Hauden: "Lamb wave transducers built on periodically poled Z-cut LiNbO3 wafers". Journal of Applied Physics, vol. 102, pp.114107, 2007.

[2] F. Bassignot, E. Courjon, G. Ulliac, S. Ballandras, J.-M. Lesage, R. Petit: "Acoustic resonator based on periodically poled transducers: Concept and analysis". Journal of Applied Physics, vol. 111, pp.064106-064106-6, 2012.

[3] F. Henrot, F. Bassignot, B. Guichardaz, G. Ulliac, E. Courjon, J.-Y. Rauch, T. Baron et S. Ballandras: "Acoustic resonator based on periodically poled lithium niobate ridge". Journal of IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control, vol. 60, pp. 1556-1563, 2013.

[4] F. Bassignot, E. Courjon, G. Ulliac, S. Ballandras, J.-M. Lesage, R. Petit: "Acoustic resonator based on periodically poled transducers: Fabrication and characterization". Journal of Applied Physics, vol. 112, pp. 074108-6, 2012.