Surface Acoustic Wave Ferroelectric Phononic Crystal Based on Electric Field Induced Periodic Domains

Vladimir P. Pashchenko [1], Sergey S. Yankin [2,3]
1. Saint Petersburg State Polytechnical University, Physics and Technology of Nanostructures Department,
29 Polytechnicheskaya street, 195251, Saint Petersburg, Russia;
2. Saratov State University, 83 Astrakhanskaya street, 410012, Saratov, Russia;
3. Joint International Laboratory LICS/LEMAC, IEMN UMR CNRS 8520,
PRES Lille North of France, EC Lille, B.P. 48, 59651, Villeneuve d'Ascq Cedex, France.

Introduction: We are propose a novel type of tunable surface acoustic waves (SAW) filter based on 1D phononic crystal controlled by electric field. The tunability of proposed filter varied over a wide range: 1-20%. Basic idea is electrical controlled induced periodical domains in ferroelectric film based on induced piezoelectric effect [1-2]. SAW filter consist of substrate with deposited ferroelectric film and series of interdigital transducers (IDT) atop of the ferroelectric film (Figure 1). Alternative electric signal apply to Input IDT and excite the surface acoustic wave. Output signal receive from Output IDT. Control DC voltage apply to Biasing IDT. Biasing voltage lead to creating the periodic domains which depend on the width of the electrodes and the voltage values. Varying the voltage and width of IDTs we can tune the SAW filter bandwidth.

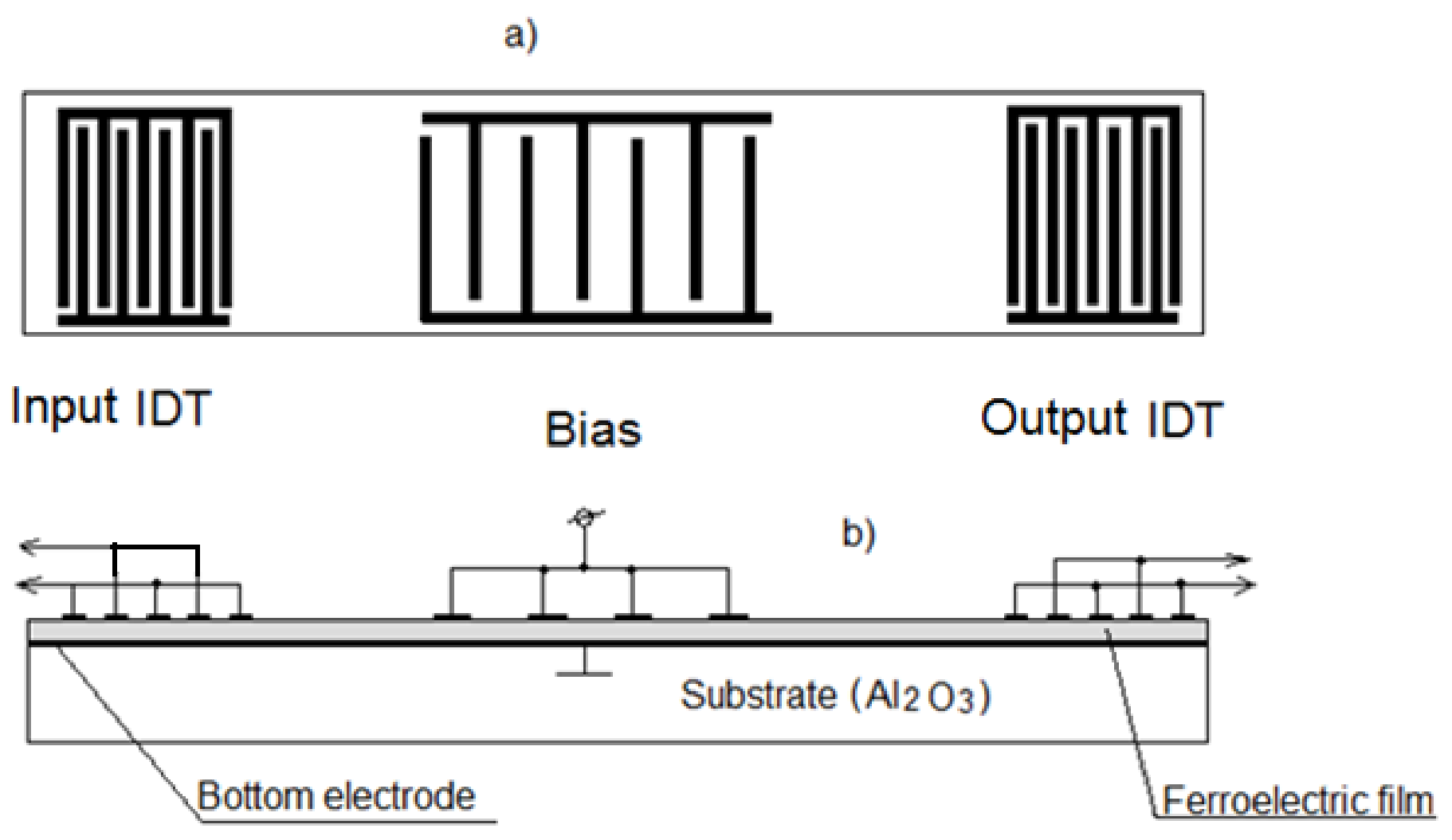

Figure 1. Tunable 1D phononic crystal (SAW filter)

Computational Methods: 2D numerical simulations using the MEMS Module of COMSOL were performed.
Equations which describe the acoustic wave propagation in anisotropic piezoelectric media:

$$\begin{cases} C_{ijmn}\dfrac{\partial^2 U_m}{\partial x_j \partial x_n} + e_{mij}\dfrac{\partial^2 \phi}{\partial x_j \partial x_m} = \rho \dfrac{\partial^2 U_i}{\partial^2 t} \\ e_{ijm}\dfrac{\partial^2 U_j}{\partial x_i \partial x_m} - \varepsilon_{ij}\dfrac{\partial^2 \phi}{\partial x_i \partial x_j} = 0 \end{cases} \qquad (1)$$

where U – mechanical displacement, ρ – ferroelectric material mass density, ϕ – electric potential, e – piezoelectric tensor.
Material constants of ferroelectric barium strontium titanate (BSTO) taken from ref [4]. IDTs material is aluminum and substrate material is sapphire.

Induced piezoeffect described by next equations [5]:

$$\begin{cases} \tilde{e}_{ijm}(E_i) = e_{ijm} - 2G_{ijmn}\varepsilon_0\varepsilon_{ij}(E_i)E \\ \tilde{C}_{ijmn}(E_i) = C_{ijmn} + M_{ijklmn}\left(\varepsilon_0\varepsilon_{ij}(E_i)E_i\right) \end{cases} \qquad (2)$$

Where e_{ijm} - piezoelectric tensor in absence of electric field (caused by defects in film), G_{ijmn}- electrostriction tensor, E_i - electric field components ($i=1,2,3$), C_{ijmn} - stiffness tensor, M_{ijklmn} - nonlinear electrostriction tensor, ε_0 vacuum permittivity, ε_{ij} - BSTO film permittivity tensor. Symbol “~” denote material parameters with biasing electric field.
Substituting (2) into (1) we obtain the system of equations which describe the elastic waves propagation in phononic crystal:

$$\begin{cases} \left\{C_{ijmn} + \varepsilon_0 \cdot \varepsilon_{ij}\left(E_i(x,y,z)\right) \cdot M_{ijklmn} \cdot \left[E_i(x,y,z)\right]^2\right\}\dfrac{\partial^2 U_m}{\partial x_j \partial x_n} + \varepsilon_0 \cdot \left[\varepsilon_{ij}\left(E_i(x,y,z)\right) - 1\right] \cdot \left\{h_{mij} - 2\varepsilon_0\varepsilon_{ij}\left(E_i(x,y,z)\right)\right\} \times \\ \times G_{ijmn} \cdot \left[E_i(x,y,z)\right]^2 \dfrac{\partial^2 \phi}{\partial x_j \partial x_m} = \rho \dfrac{\partial^2 U_i}{\partial t^2}; \\ \varepsilon_0 \cdot \left[\varepsilon_{ij}\left(E_i(x,y,z)\right) - 1\right] \cdot \left\{h_{mij} - 2\varepsilon_0\varepsilon_{ij}\left(E_i(x,y,z)\right) \cdot \dfrac{\partial^2 U_j}{\partial x_i \partial x_j} - \varepsilon_{ij}\left(E_i(x,y,z)\right)\right\} \cdot \dfrac{\partial^2 \phi}{\partial x_i \partial x_j} = 0 \end{cases} \qquad (3)$$

For solving equations (3) the problem was divided into two steps. At the first step an electric field distribution has been found by solving the electrostatic problem. At the second step the piezoelectric problem was solved using the electric field distribution stored at previous step. Computation methods for solving SAW problem were taken from ref [3]. Input IDT excited SAW from 490 to 520 MHz bandwidth. Bias IDT has center frequency 500 MHz which defined by *fc = V/(2p)*, where *V* and *p* are SAW velocity in structure and IDT period respectively. Bias IDT electrodes width chosen as *p/2*. Period *p* is equal the SAW wavelength. Model depict in Figure 2. Thus *p/2* satisfies the Bragg condition and *fc* is forbidden frequency. Number of electrodes in Bias IDT is 80. Number of Input IDT and Output IDT are 40. For wide band SAW exciting modeling were performed sweeping of IDT period variable *p*. The substrate edges are rounded to prevent SAW reflections. Also were simulated problem consisted of 1 period of phononic crystal with Floquet boundary conditions for band gaps estimation (Figure 3). Boundary conditions present at Table 1.

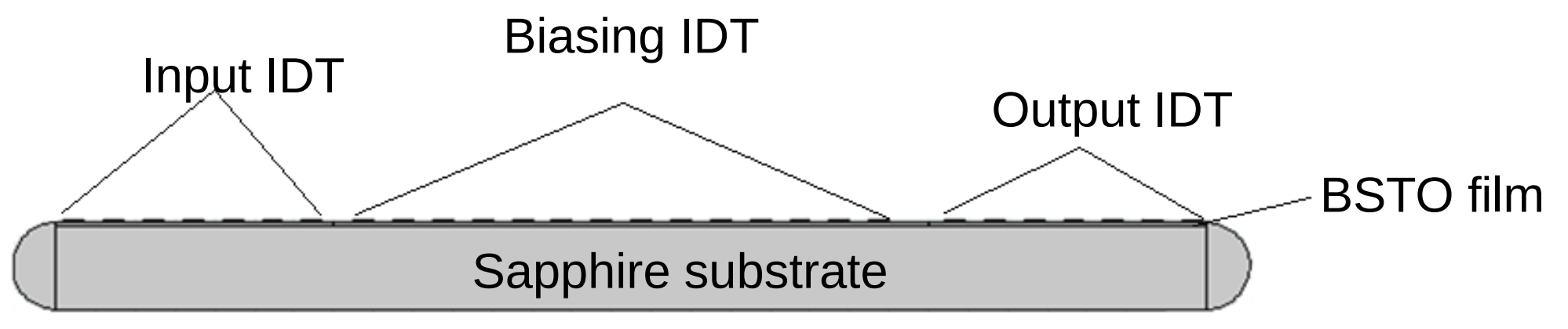

Figure 2. COMSOL simulation model of tunable SAW filter

Table 1. Boundary conditions

Number of boundary	Boundary condition
1	Floquet X - direction
2	Terminal
3	Fixed. Ground

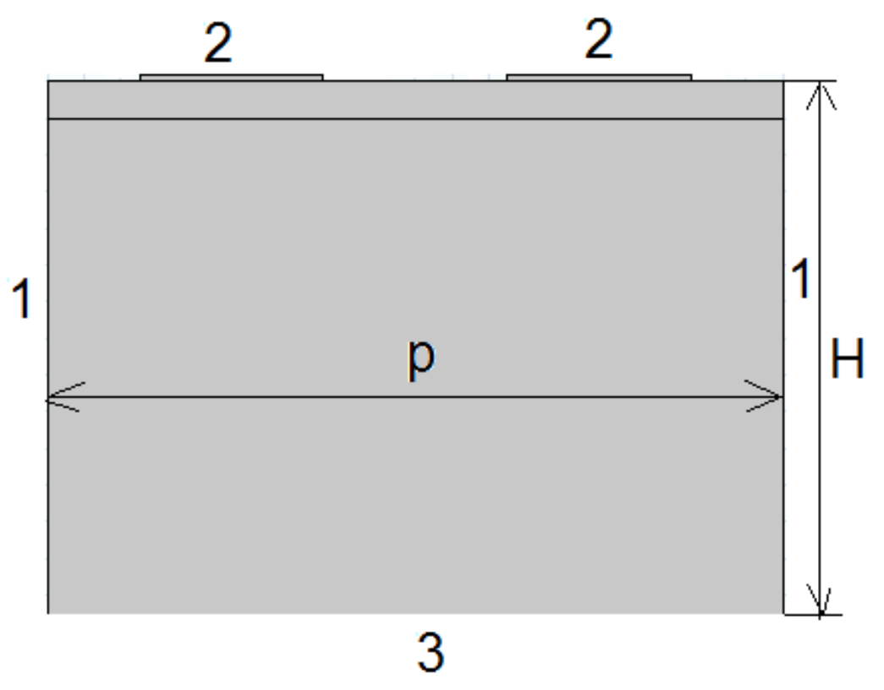

Figure 3. 1 period of phononic crystal.

Results: Results of the electric field distribution (fragment) under Biasing IDT equal width depicted in Figure 4. It can be see that there are edge effects on the electrodes and electric field distribution is not homogenous. These effects can be taking into account due to numerical simulation only. Phononic crystal transmission coefficient as frequency function shown in Fig. 5. The phononic crystal stopband is about 7 MHz.
Surface acoustic wave excitation in 1D phononic crystal shown in Figure 6. In Figures 7-8 presented dispersion curves of phononic crystal with various Biasing IDT electrodes width and electric field respectively.

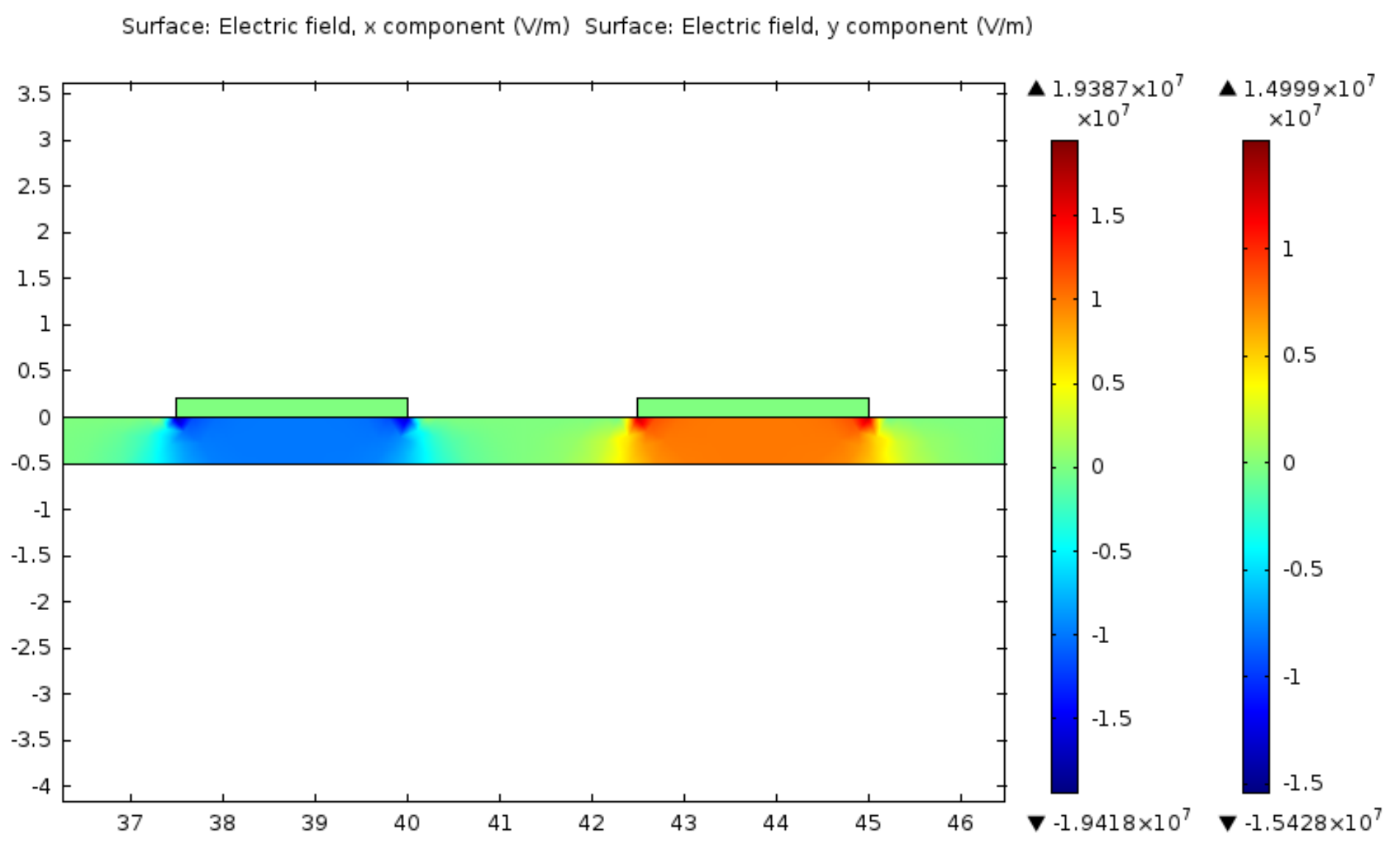

Figure 4. Electric field (X and Y component) distribution in phononic crystal. Bias 5 Volts corresponds to 10 MV/m electric field.

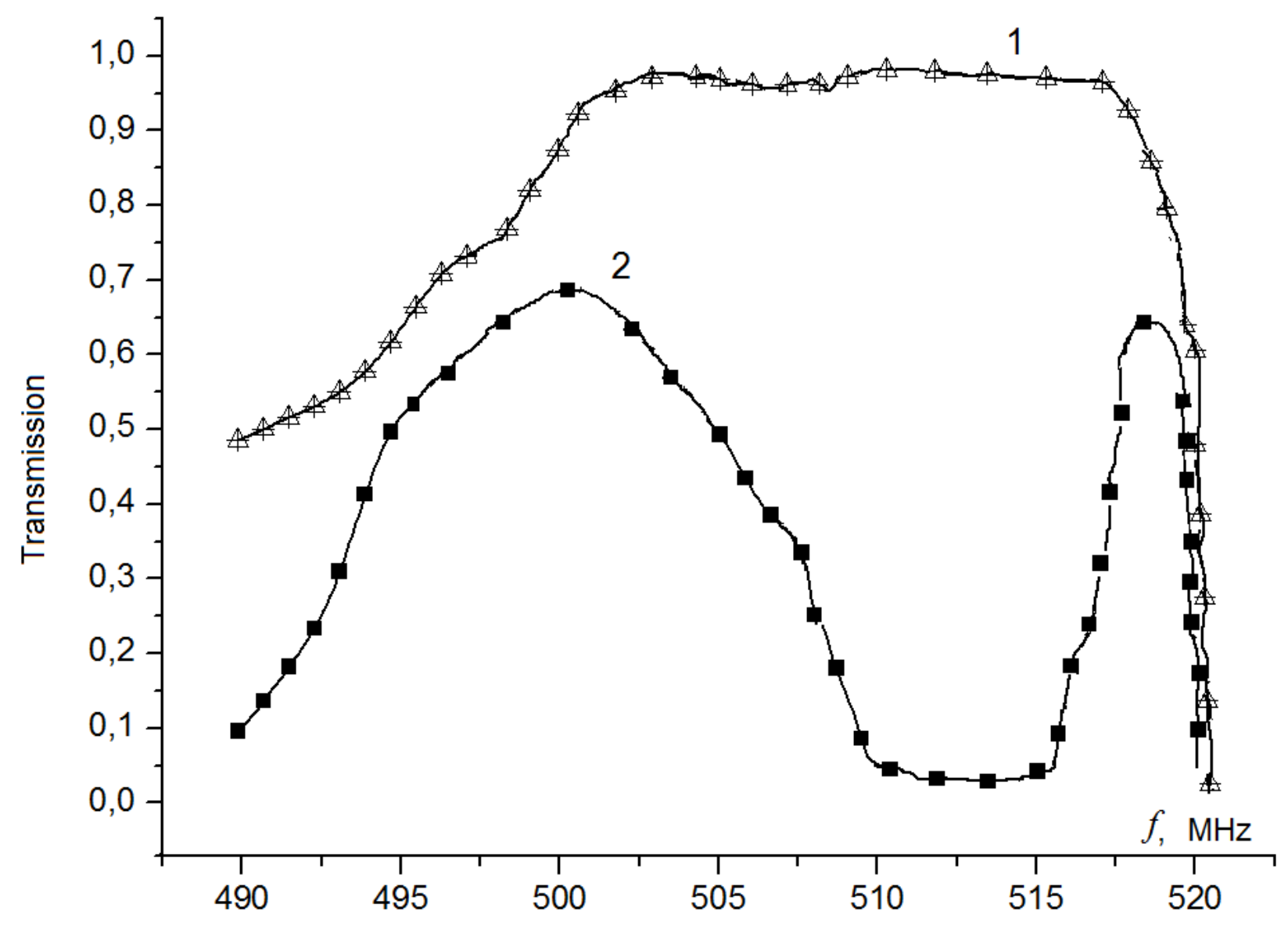

Figure 5. SAW transmission versus frequency in phononic crystal.
1 – Biasing voltage 0 V
2 – Biasing voltage 5 V

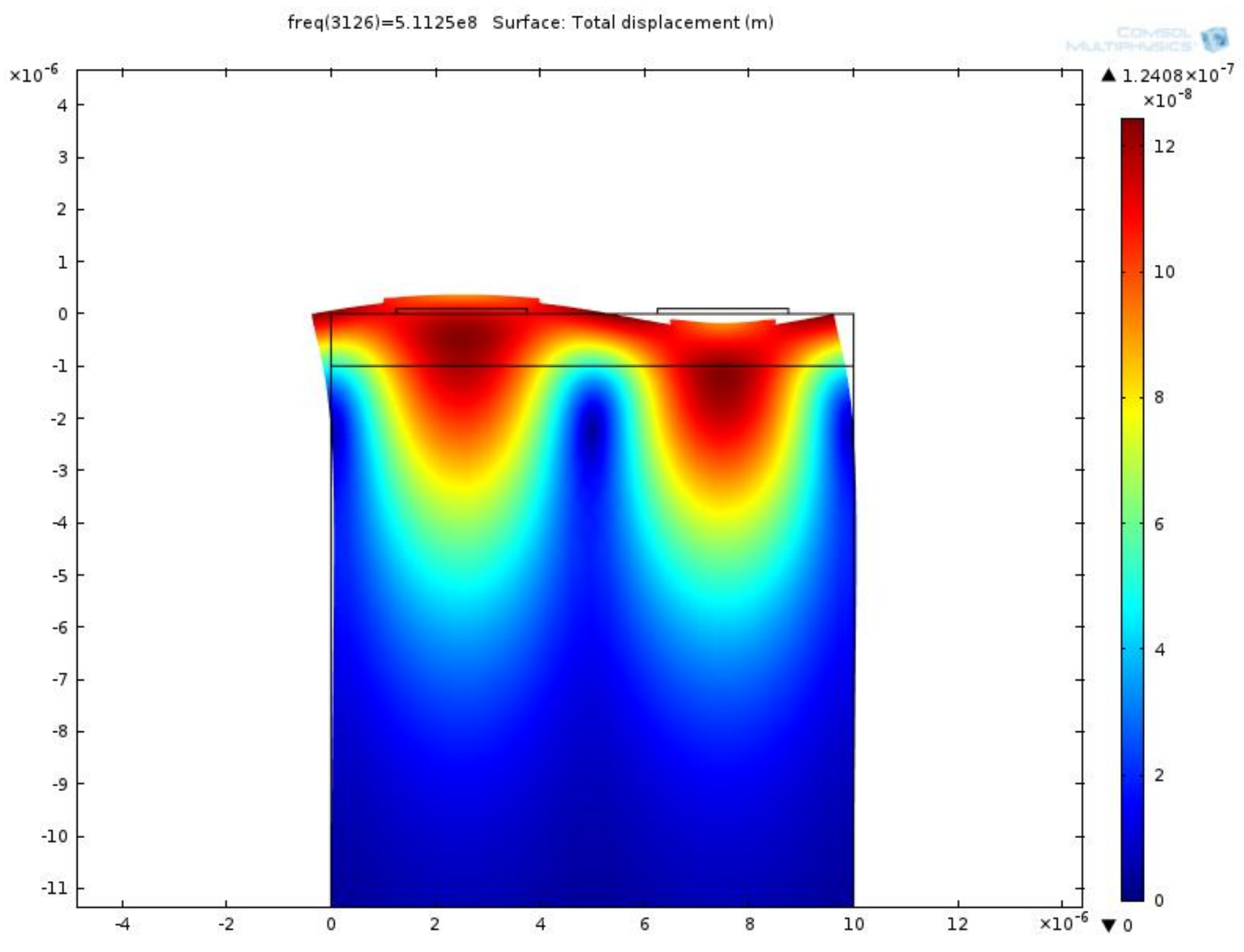

Figure 6. SAW excitation. Displacement amplitude

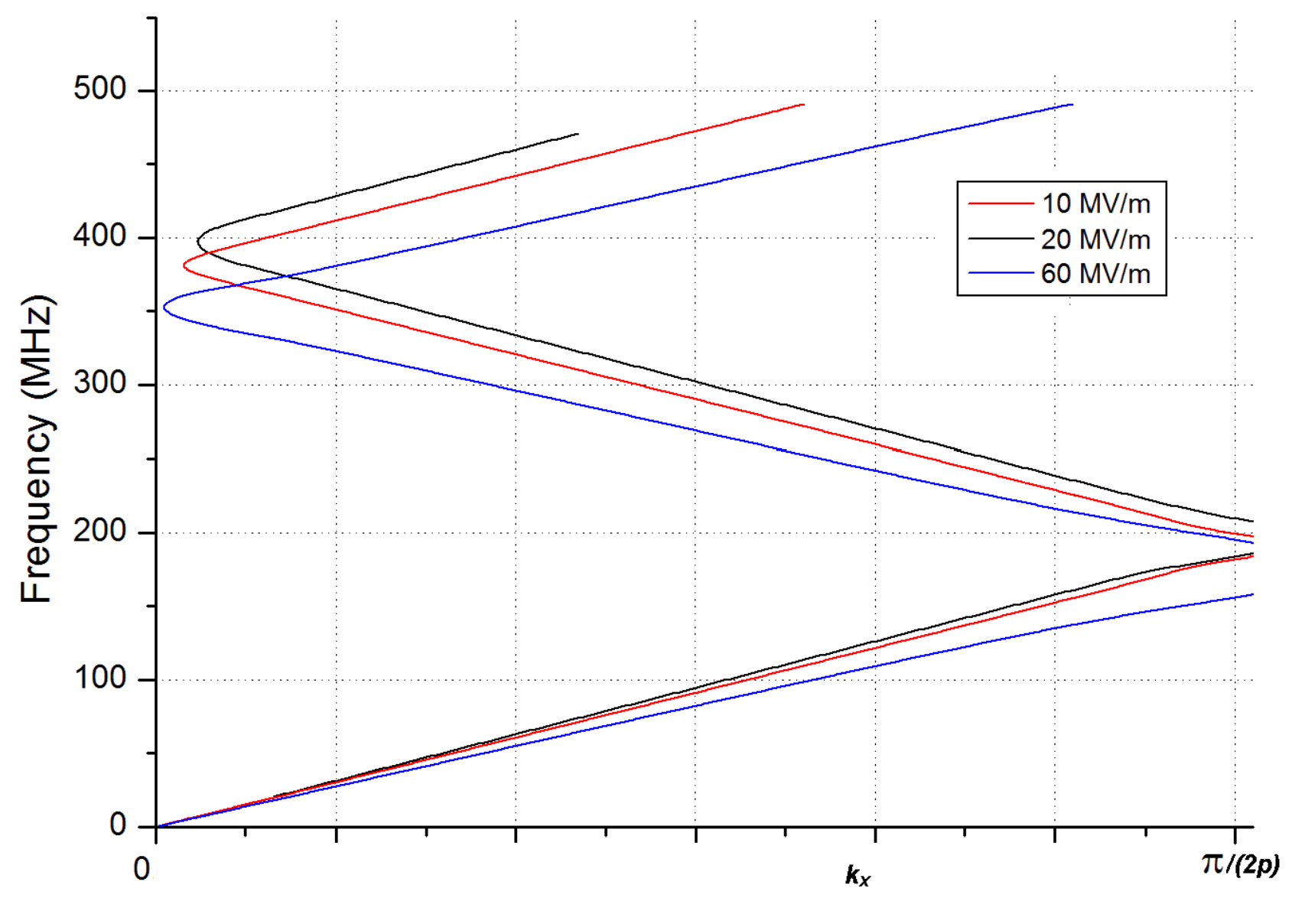

Figure 7. Band gaps tunability depended on electric field

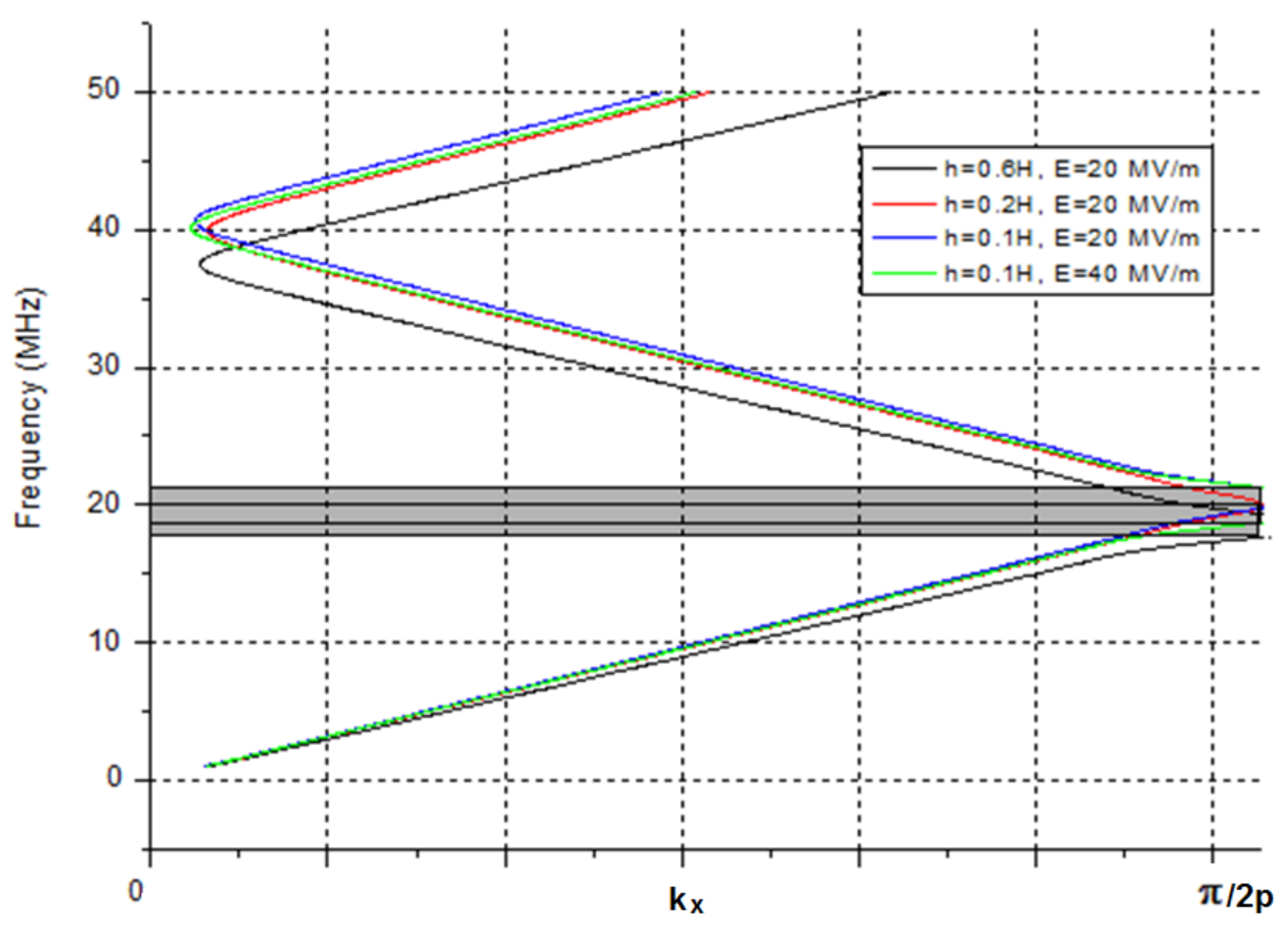

Figure 8. Band gaps tunability depended on electric field and electrodes width

Conclusions: Finite-element modeling in COMSOL software revealed presence of the phononic band gap for surface acoustic waves in structure consisting of electrically induced periodic ferroelectric domains. This effect can be used in tunable surface acoustic wave filters.
Shown three way for tuning the phononic crystal:

1. Varying the biasing voltage (equal width of Biasing IDT electrodes)
2. Varying the width of Biasing IDT electrodes (equal Biasing voltage)
3. Both varying biasing voltage and electrodes width

Maximum achieved tunability is 20%. For reducing the influence of the electrodes on surface of wave propagation it is expedient to consider other types of waves for example such guided wave, Love waves or Stoneley waves. The experimental verification of the simulation results will be conducted in future.

References:

1. Pavel Turalchuk, Irina Vendik, Orest Vendik, John Berge, Electrically Tunable Bulk Acoustic Filters with Induced Piezoelectric Effect in BSTO Film, Proceedings of the 38th European Microwave Conference, P. 274 – 277 (2008)
2. Berge John, Tunable Bulk Acoustic Wave Resonators Based on Ba0.25Sr0.75TiO3 Thin Films and a HfO2/SiO2 Bragg Reflector, IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control, Volume 58, P. 2768 – 2771, (2011)
3. R. Krishnan, H.B. Nemade, and R. Paily, Simulation of a One-Port SAW Resonator using COMSOL Multiphysics, Excerpt from the Proceedings of the COMSOL Users Conference (2006)

Excerpt from the Proceedings of the 2013 COMSOL Conference in Rotterdam