Energy Harvesting with lead free $LiNbO_3$

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***Abstract*—$LiNbO_3$ crystals and thin films are investigated for energy harvesting vibrational motion under low frequency (<100 Hz). The geometrical parameters and crystal orientations of the piezoelectric element are investigated by finite element software (FEM) in order to maximize the figure of merit. In addition, the structure of the device is simulated in a bending cantilever, including electrodes and resistance loading. The $LiNbO_3$ crystal orientation is investigated under transverse excitation mode.**

I. INTRODUCTION

Lead-free piezoelectric transducers and energy harvesters are intensively investigated to replace Lead Zirconate Titanate (PZT) due to EU Regulation. Zinc oxide (ZnO) piezoelectric has been studied in the form of films or nanowires. However, more complex oxides like Lithium Niobate ($LiNbO_3$) present several advantages such as high chemical stability, high temperature stability (Curie temperature is 1198°C [1]) and high electromechanical coupling. Even though $LiNbO_3$ has been widely studied in optics and surface acoustic waves field, little investigations have been done concerning its application for energy harvesting. High quality 6-inch wafers are sold for relative low price, allowing mass production of custom orientation cuts wafer. Moreover, $LiNbO_3$ can be found in ions slide film on silicon, grown epitaxially by MOCVD with different orientations [2]. Meanwhile, as compared to cubic PZT, the strong anisotropic piezoelectric, dielectric and mechanical properties have to be investigated. Moreover, one of the constraints in vibration energy harvesting, is its ability to harvest low frequency vibrations.

For instance, from the signal recorded with triaxial accelerometer in a car driving along an urban road, is possible to study acceleration levels (see Real Vibrations database [3]). If we take the signal when the sensor is positioned on the steering wheel of a diesel car, with gravity along x-axis, we can find that the root mean squared value of the signal is Xrms=0.52g, where g=9.81m/s^2. Once performed spectrogram analysis, it appears that the strongest frequency response intensity is below 40Hz. These vibrations are due to the running engine, and we can assume that this frequency is dominant and stationary. In this case it is possible to use a cantilever device to exploit vibrations as a source of kinetic energy.

One of the most common way to harvest energy is done by exploiting transverse piezoelectric mode in cantilevered beam configuration. The strain and electrical field are related by the constitutive relations:

$$\begin{cases} S_1 = s_{11}^E T_1 + d_{31} E_3 \\ D_3 = d_{31} T_1 + \epsilon_{33}^T E_3 \end{cases} \qquad (1)$$

where S is the strain tensor, s^E is compliance fourth order tensor at constant electric field, T is the stress tensor, d is the third order piezoelectric tensor, E is the electric field vector, D is the dielectric displacement vector and ϵ^T is the permittivity at constant stress. Here, charges are collected in transverse excitation mode with top-bottom electrodes, where '3' is polarization direction, while the piezoelectric element undergoes strain in '1' direction. The coupling factor k_{31} is the efficiency of transduction from mechanical to electrical energy, and for transverse mode it is described by (Eq. 2):

$$k_{31}^2 = \frac{d_{31}^2}{s_{11}^E \epsilon_{33}^T} \qquad (2)$$

II. ORIENTATION STUDY OF LITHIUM NIOBATE

$LiNbO_3$ has a trigonal structure R3c. It presents piezo-, pyro- and ferro-electrical properties and strongly anisotropic dielectric, mechanical properties represented in tensor form. The value of these tensors are well documented [4].

In transverse excitation mode, the rotation of the piezoelectric tensor shows that not only d_{31} will contribute to the piezoelectric response, but other coefficients as well. In order to have optimal values for the piezoelectric coefficients, we investigate the effect of rotation of the crystal. In Fig. 1, the rotation of piezoelectric tensor around x-axis by ψ angle shows strong variation of piezoelectric coefficients. The best configuration is achievable with Y-128° wafer cut, where we find higher d_{23}=27pC/N, and higher coupling factor k_{23}=0.45.

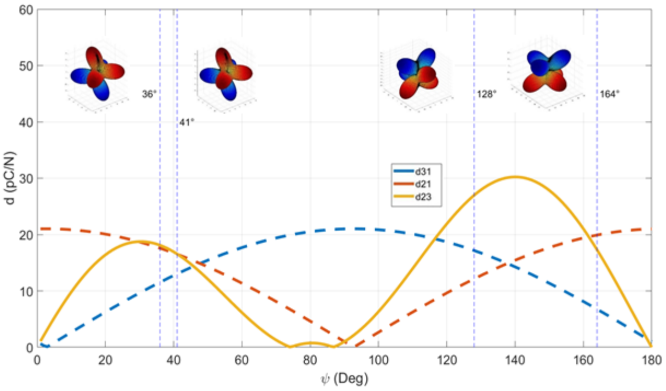

FIGURE 1. ORIENTATION STUDY OF $LiNbO_3$ PIEZOELECTRIC TENSOR

III. FINITE ELEMENT MODELING

In order to test the validity of our energy harvester, we designed a 3D unimorph cantilevered beam for eigen-frequency analysis, and then a 2D model for frequency domain analysis. Our proposed device is smaller than 1 cm^3, whose dimensions and 3D representation are reported in Fig. 2. The acceleration level is introduced as a parameter to simulate the excitation inside the car (0.5g).

Cantilver dimensions (µm)		
Length	Width	Thickness
7E3	2E3	20
Tip mass dimensions (µm)		
2E3	2E3	400

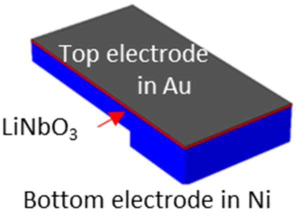

FIGURE 2. DIMENSIONS AND CONFIGURATION OF PIEZOEELCTRIC CANTILEVER

$LiNbO_3$ is the piezoelectric element for electromechanical conversion (1µm thickness). The hosting structure and mass load are made of nickel and the top contact is a gold electrode. Parametric sweep is performed to implement simulation on $LiNbO_3$ orientation and optimal load.

IV. RESULTS

The eigen-frequency analysis allows to find the resonance frequency of our system, whereas the first mode is the bending mode (Fig. 3). The value computed is 35Hz, although other modes can be found at higher frequency (>100Hz). Bending mode value is in the same range as the one found in the experimental data.

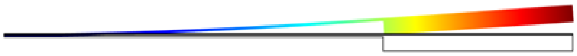

FIGURE 3. BENDING MODE OF CANTILEVER

While voltage response is investigated in the frequency domain, parametric sweep is performed to implement the orientation study for $LiNbO_3$ piezoelectric element (Fig. 4).

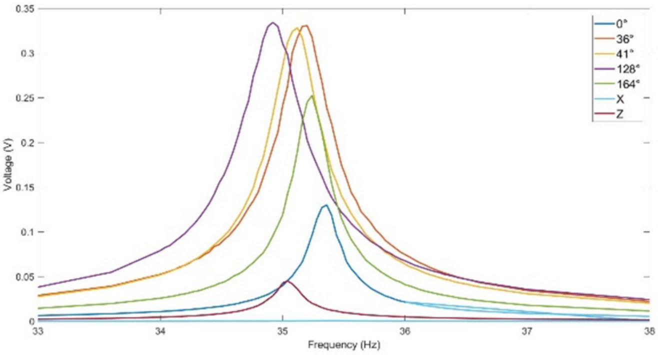

FIGURE 4. VOLTAGE RESPONSE FOR DIFFERENT ORIENTATIONS

The response of the device is centered around 35Hz as expected. The maximum amplitude is found at Y-128° orientation and leads to 0.34V with a load of 200kΩ. These values are in good agreement with the orientation study presented in Fig. 2. Moreover for Y-36°, orientation close to epitaxial thin-film [2], we have encouraging result in terms of voltage.

Finally it is possible to study voltage and power harvested varying the resistive load coupled with our cantilever. In this case the simulation allows to investigate the maximum power-point (Fig. 5). Maximum efficiency is reached when the cantilever resonates at 35Hz and its orientation is Y-128°. The power harvested is 340nW at 150kΩ with an output voltage of 0.3V, and the figure of merit is about $10\mu W/cm^2/g^2$.

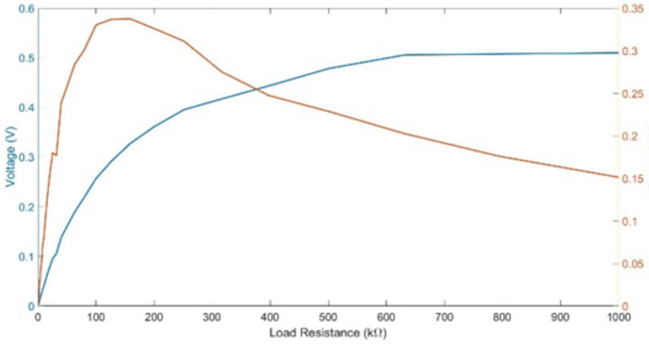

FIGURE 5. OPTIMAL LOAD FOR POWER AND VOLTAGE STUDY

V. CONCLUSION

A piezoelectric cantilever is a suitable choice for vibrational energy harvesters exploiting low frequency vibrations in cars. Y-128° $LiNbO_3$ cut presents high piezoelectric coefficient (d_{23}=27pC/N) and coupling (k_{23}=0.45). Modeling the cantilever with FEM allows to investigate power and voltage generated, but further optimization is needed in order to obtain higher figure of merit.

References

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