Optimization of Pockels effect in poled amorphous waveguides for efficient electro-optic modulation

SIRAWIT BOONSIT[1], VASILEIOS MOURGELAS[1], LARA KARAM[2], MILOS NEDELJKOVIC[1], NADEGE COURJAL[3], MARC DUSSAUZE[2] AND GANAPATHY SENTHIL MURUGAN[1]

1 Optoelectronics Research Centre, University of Southampton, Southampton, SO17 1BJ, United Kingdom
2 Institut des Sciences Moléculaires, Université de Bordeaux, Talence Cedex 33405, France
3 FEMTO-ST TEMIS, 15B avenue des Montboucons, BESANCON Cedex 25030, France *sb5e21@soton.ac.uk

Motivation

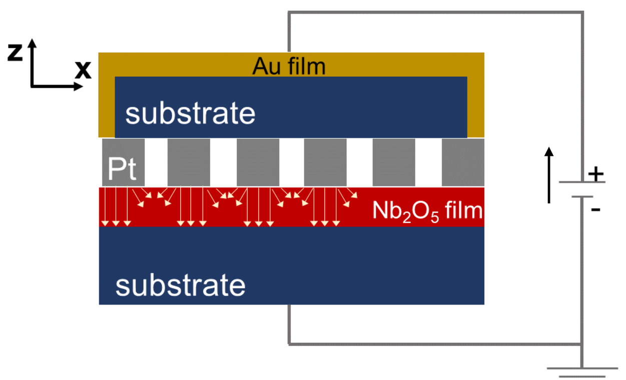


Figure. 1. The diagram shows the patterned poling of a Nb_2O_5 thin film

- **Crystalline materials** are renowned for their strong nonlinear response ($\chi^{(2)}$) but encounter fabrication challenges such as low index contrast in traditional diffused lithium niobate waveguides and difficulty in etching for lithium niobate-on-insulator platform [1]. In contrast, **amorphous materials** offer fabrication flexibility due to their isotropic nature but lack inherent second-order nonlinear response. Nonetheless, this deficiency can be addressed through techniques such as **thermal poling**. Recently, inducing nonlinearity in materials like sodium-doped niobium oxide (Nb_2O_5) thin films have shown promising results ($\chi^{(2)} = 29\ V.cm^{-1}$, comparable to lithium niobate) [2,3].

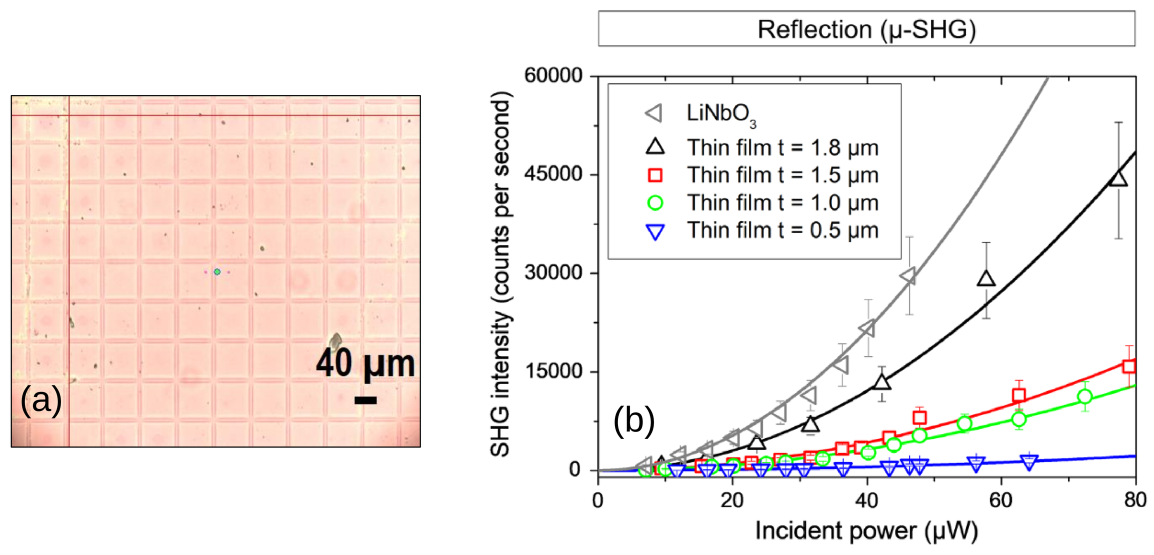


Figure. 2. Surface of Sodium-doped Nb_2O_5 poled film (a) and SHG intensity as a function of the incident power for the films of different thicknesses measured by specular reflection SHG microscopy (b) [2]

State of the art

- Electro-optic modulators (EOMs) are vital in optical communication systems, offering precise control over optical signals. Traditionally, they rely on materials exhibiting the electro-optic effect, like lithium niobate ($LiNbO_3$), known for strong coefficients. However, their fabrication complexity and bulky components hinder integration into compact photonic circuits.
- Nb_2O_5 thin films, characterized by broad transparency, a high refractive index (~2.1-2.2) at 1550 nm, and significant induced ($\chi^{(2)}$), emerge as promising candidates for advanced waveguide platforms

Objectives

- Design and optimize the EO phase modulator based on Nb_2O_5 strip and rib waveguides
- Examine two poling configurations: homogenous and patterned poling
- Assess influence of poling direction on optical field using both TE and TM polarizations
- Achieve lowest possible voltage-length product ($V_\pi L$) for EO phase modulators.

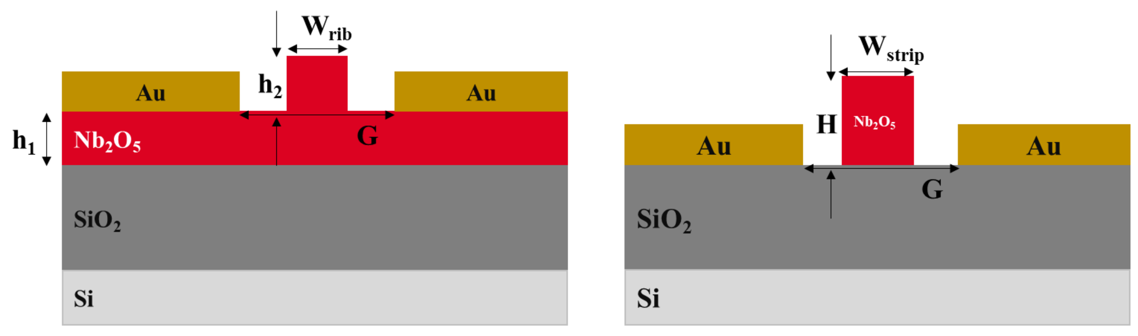


Figure 3. The diagram shows the model of rib waveguide (left) and strip waveguide (right) with labelled parameters

Simulation Procedure

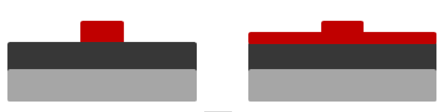
- Refractive index deformation due to external electric field:
  - **Homogeneous poling:**

$$\left(\frac{1}{n_x^2} - r_{13}E_z\right)x^2 + \left(\frac{1}{n_y^2} - r_{13}E_z\right)y^2 + \left(\frac{1}{n_z^2} - r_{33}E_z\right)z^2 - 2xzr_{13}E_x = 1$$

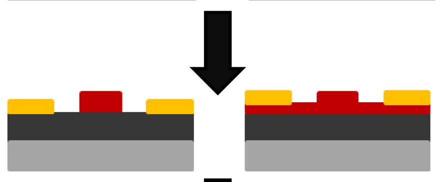
  - **Patterned poling:**

$$\left(\frac{1}{n_x^2} - r_{11}E_x - r_{13}E_z\right)x^2 + \left(\frac{1}{n_y^2} - r_{21}E_x - r_{13}E_z\right)y^2 + \left(\frac{1}{n_z^2} - r_{21}E_x - r_{33}E_z\right)z^2 - 2xz(r_{13}E_x + r_{21}E_z) = 1$$

(1) Single mode waveguide dimensions



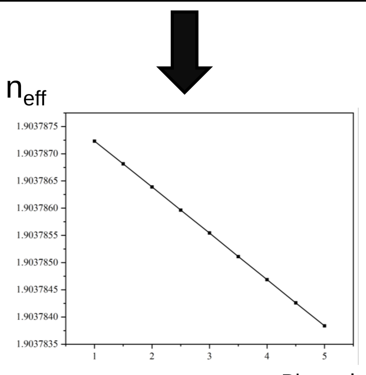
(2) Optimising electrode gap (loss ~dB/cm)



(3) Apply the DC electric field 1-5 V

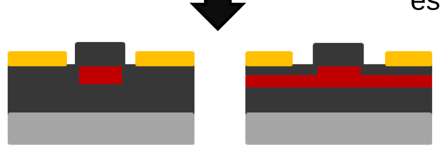
(4) Calculate the refractive index change from homogenous poling and structured/patterned poling

(5) Simulate optical mode at 1.55 μm and calculate Δn_{eff} vs DC voltage



(6) Estimate the voltage-length product FOM value

(7) Add SiO_2 top cladding and estimate the voltage-length product



Simulation results

Single mode waveguide

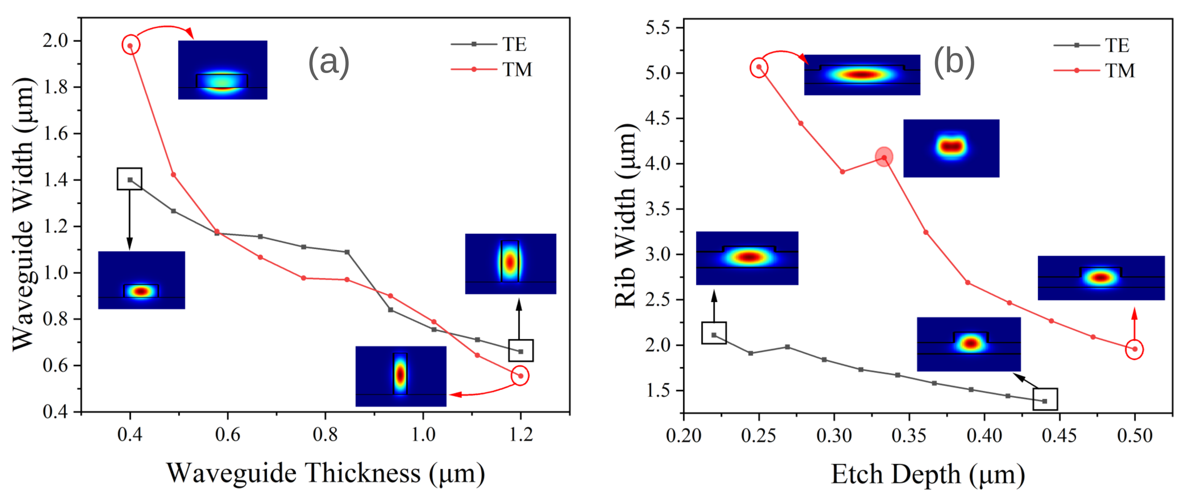


Figure. 4. Single mode dimensions of Strip waveguide (a), Rib waveguide (b) for both TE and TM modes

Field confinement factor

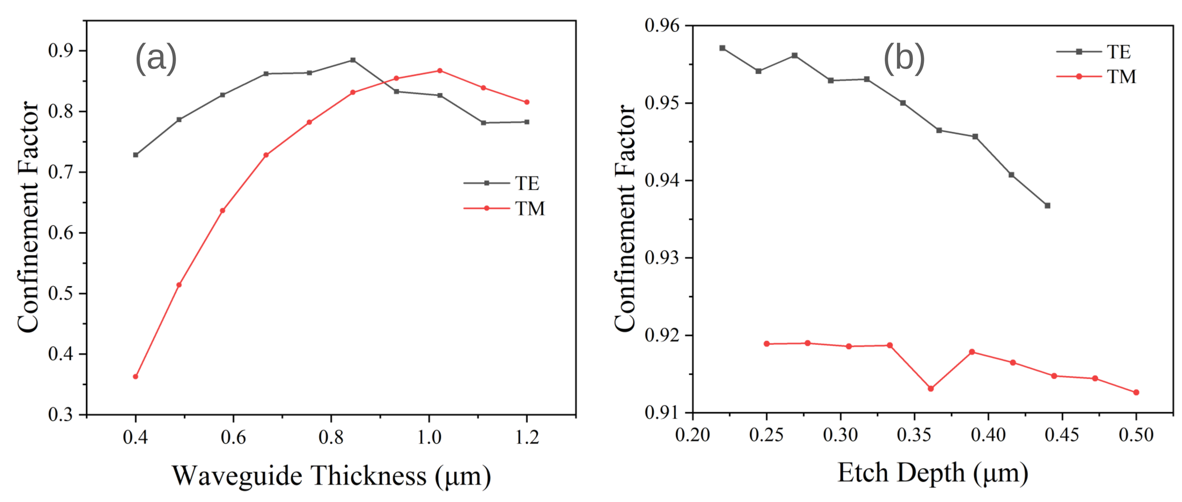


Figure. 5. Field confinement factor of Strip waveguide (a) and Rib waveguide (b) for each single mode waveguide dimension

Optimizing the electrode gap

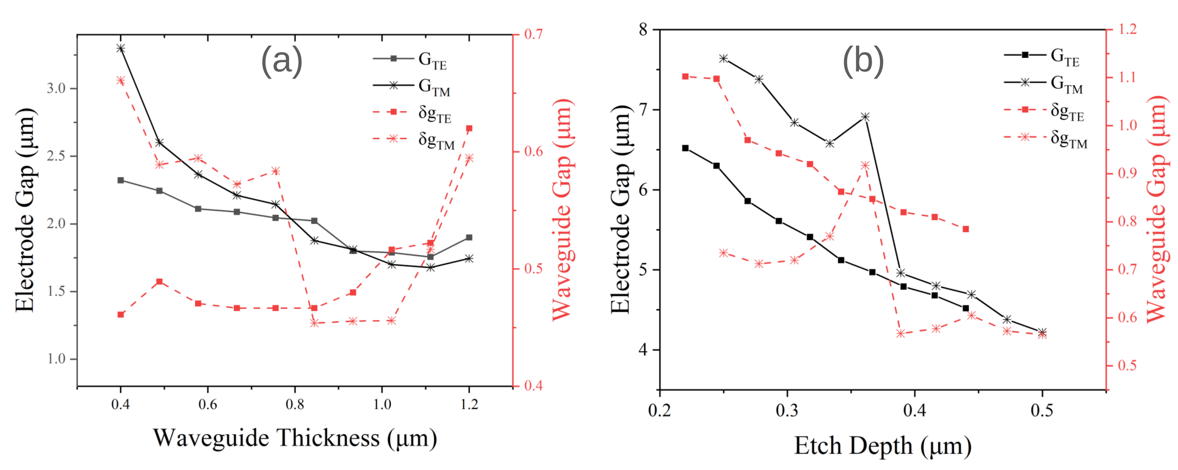


Figure. 6. Plot of gap between anode and cathode (G) for a loss of 1 dB/cm and the gap between waveguide and electrode (δg) for a Strip waveguide (a) and a Rib waveguide (b) for each single mode waveguide dimension

Electric field distribution, change of effective index

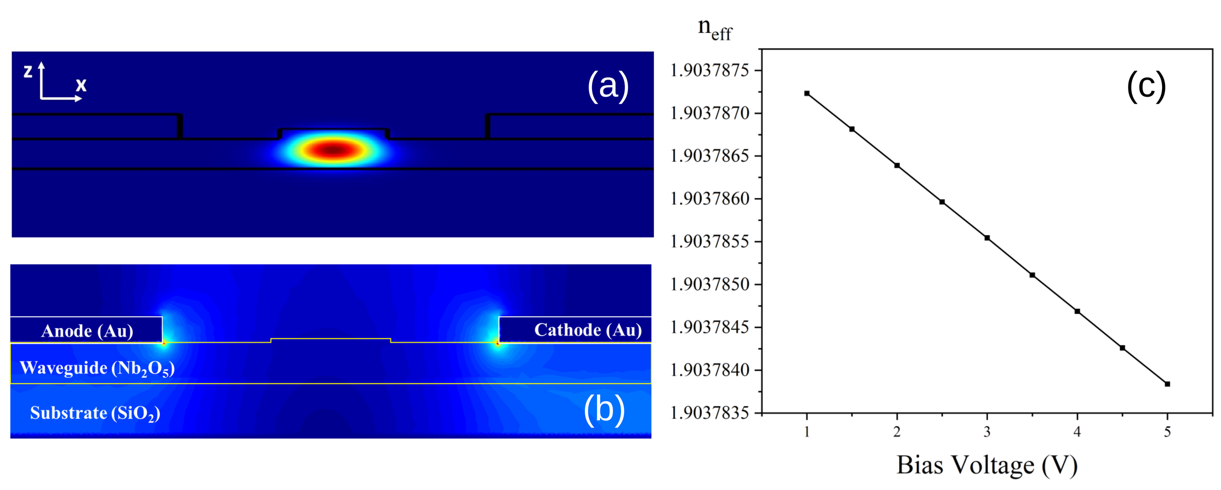


Figure. 7. (a) Cross section of fundamental TE mode distribution in the rib waveguide. (b) DC electrical field distribution at 1,1.5,2,2.5,3,3.5, 4, 4.5 and 5 V. (c) Effective refractive index change due to the applied voltage

Including SiO_2 top cladding

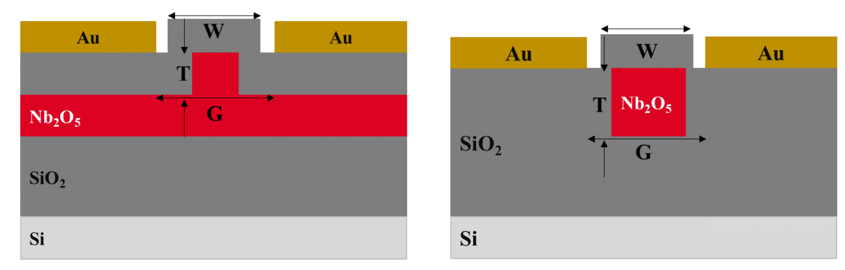


Figure. 10. Diagram of Rib (left) and Strip (right) waveguide with SiO_2 cladding

Waveguide	W (μm)	T (μm)	Gap (μm)	δg (μm)	Loss (dB/cm)	$V_\pi L$ (V.cm)
Strip	-	-	2.1	0.45	~1	18.8
Strip with top cladding	1.5	0.88	2.1	0.45	0.17	16.9
			1.6	0.25	2	12
Rib	-	-	4.5	0.80	~1	45.6
Rib with top cladding	1.8	0.5	4.5	0.80	0.0005	46.4
			2.2	0.41	0.30	18.6
			1.9	0.26	1.82	14.6

Table 1. Summary of voltage-length product of strip and rib waveguide with/without top SiO_2 cladding

Conclusions

- Strip waveguide (0.88 µm thick, 1 µm wide) demonstrated significant modulation with figure of merit ($V_\pi L$) of 20 V.cm, attributed to TE polarization interaction.
- Rib waveguides showed nearly two-fold lower performance (45 V.cm) due to wider electrode gaps.
- Addition of SiO_2 cladding layer improved efficiency (17 V.cm for strip, 19 V.cm for rib).
- Future work will focus on fabricating the EO phase modulator with induced nonlinearity of Nb_2O_5.

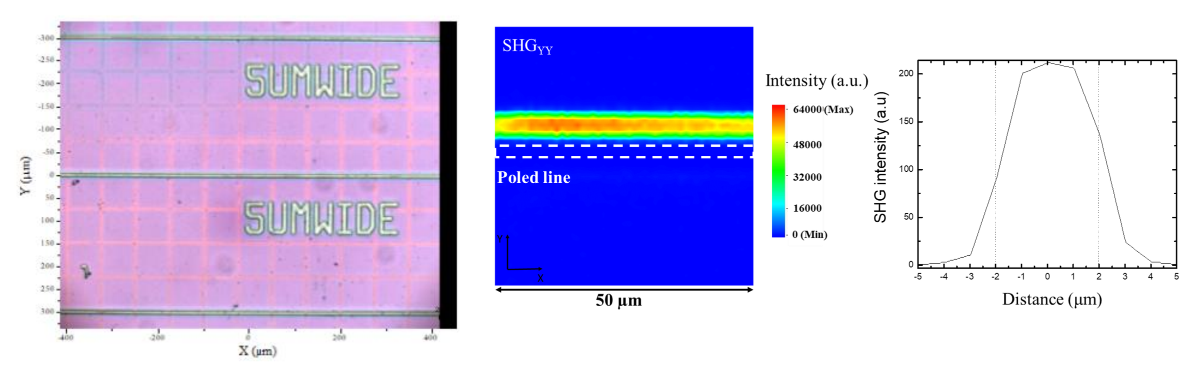


Figure. 11. Induced Second Harmonic Generation (SHG) signal showing the sustainability of induced optical nonlinearity through waveguide fabrication.

Funding

This work was supported by "The Future Photonics Hub" (EPSRC grant EP/N00762X/1).
SB thanks the Thailand government for his PhD studentship.

References

1. Wang C, Zhang M, Chen X, Bertrand M, Shams-Ansari A, Chandrasekhar S, et al. Integrated lithium niobate electro-optic modulators operating at CMOS-compatible voltages. 2018;562(7725):101-4.
2. Karam, L., F. Adamietz, D. Michau, et al., Second-Order Optical Response in Electrically Polarized Sodo-Niobate Amorphous Thin Films: Particularity of Multilayer Systems. Advanced Photonics Research, 2021. 2(6): p. 2000171.
3. Karam, L., F. Adamietz, D. Michau, et al., Electrically micro-polarized amorphous sodo-niobate film competing with crystalline lithium niobate second-order optical response. Advanced optical materials, 2020. 8(13): p. 2002202.
4. Verbiest, T., K. Clays, and V. Rodriguez, Second-order nonlinear optical characterization techniques: an introduction. 2009: CRC press

Modulating efficiency, voltage-length product

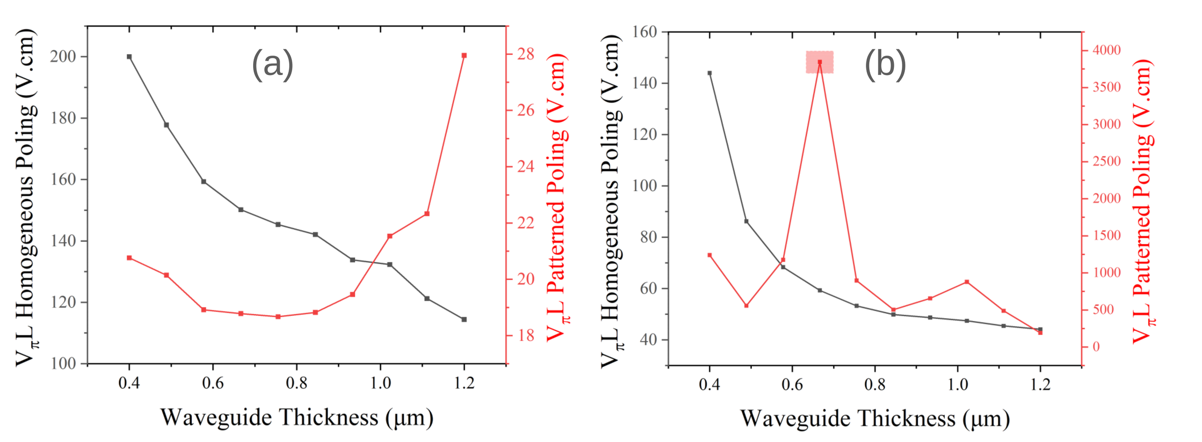


Figure. 8. Voltage-length product of single mode dimensions of Strip waveguide (a) TE (b) TM modes for both poling conditions

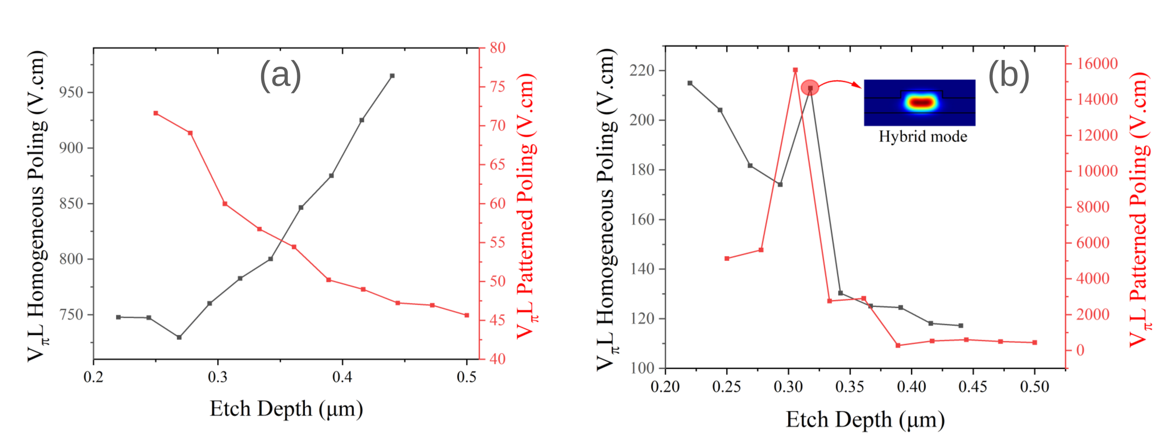


Figure 9. Voltage-length product of single mode dimensions of Rib waveguide (a) TE (b) TM modes for both poling conditions