Barium Titanate: An emerging ferroelectric material for efficient electro-optic modulation

M Ifaz Ahmad Isti[1*], Xiaofeng Zhu[1] , Marco Tulio Moller de Freitas [1], Peng Yao[2], Shouyuan Shi[1,2], M. Jobayer Hossain[2], Timothy Creazzo[2], and Dennis Prather[1,2]

[1]Electrical and Computer Engineering Dept, University of Delaware, Newark, DE, [2]Phase Sensitive Innovations, Inc., 116 Sandy Dr, Newark. DE.

Introduction

- Miniaturization of photonic structures, ensuring very low power consumption, and implementing them in a photonic integrated platform is an urgency nowadays when it comes to high-speed data transmission efficaciously for long-haul fiber optic communications. For that, electro-optic modulators are the means to attain that.
- Lithium Niobite is one of those versatile materials that has gained high popularity in the recent past when it comes to designing photonic platforms. However, the application of lithium niobite as a bulk material certainly limits its potential dormant.
- Barium titanate, BaTiO3 (BTO), has emerged as a promising electro-optic material because of its ultra-high electro-optic Pockel's coefficient.

Electro-Optic Effect in BTO

When an external electric field E is applied on as single crystal, the index ellipsoid $(n_{ij}(0) + \Delta n_{ij})x_i x_j = 1$ is deformed

$$\left[\frac{1}{n_x^2}+\Delta\left(\frac{1}{n^2}\right)_1\right]x^2+\left[\frac{1}{n_y^2}+\Delta\left(\frac{1}{n^2}\right)_2\right]y^2+\left[\frac{1}{n_z^2}+\Delta\left(\frac{1}{n^2}\right)_3\right]z^2 +2\Delta\left(\frac{1}{n^2}\right)_4 yz+2\Delta\left(\frac{1}{n^2}\right)_5 xz+2\Delta\left(\frac{1}{n^2}\right)_6 xy=1$$

$$\text{where } \Delta\left(\frac{1}{n^2}\right)_i=\sum_{j=1}^{3} r_{ij}E_k=\begin{pmatrix} r_{11} & r_{23} & r_{13}\\ r_{21} & r_{22} & r_{23}\\ r_{31} & r_{32} & r_{33}\\ r_{41} & r_{42} & r_{43}\\ r_{51} & r_{52} & r_{53}\\ r_{61} & r_{62} & r_{63}\end{pmatrix}\begin{pmatrix} E_x\\ E_y\\ E_z\end{pmatrix}$$

Due to crystal symmetry of BTO

$$r_{\mathrm{BaTiO_3}}=\begin{pmatrix} 0 & 0 & r_{13}\\ 0 & 0 & r_{23}\\ 0 & 0 & r_{33}\\ 0 & r_{42} & 0\\ r_{51} & 0 & 0\\ 0 & 0 & 0\end{pmatrix}$$

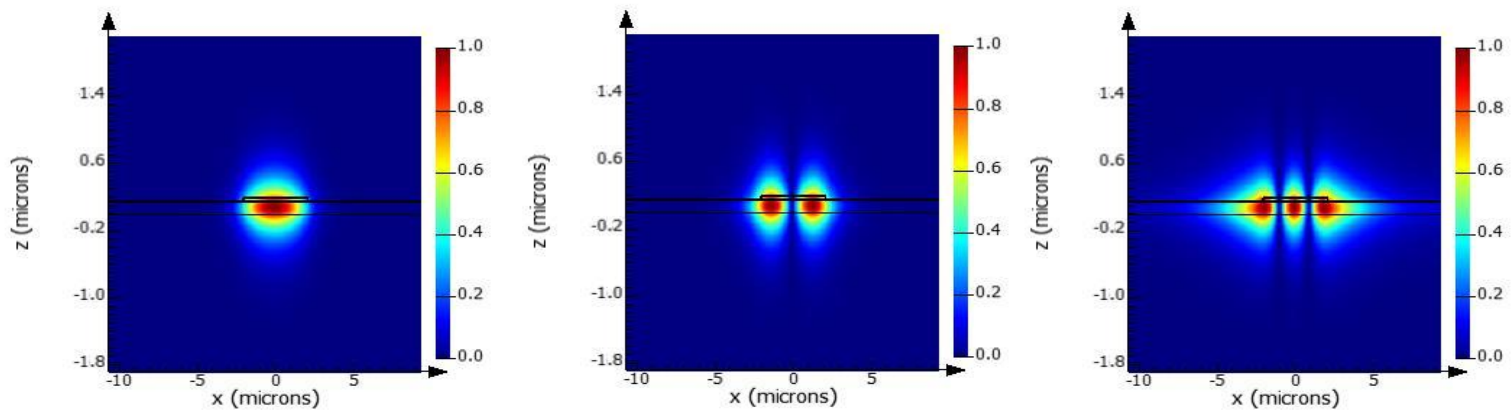
Theoretical Considerations

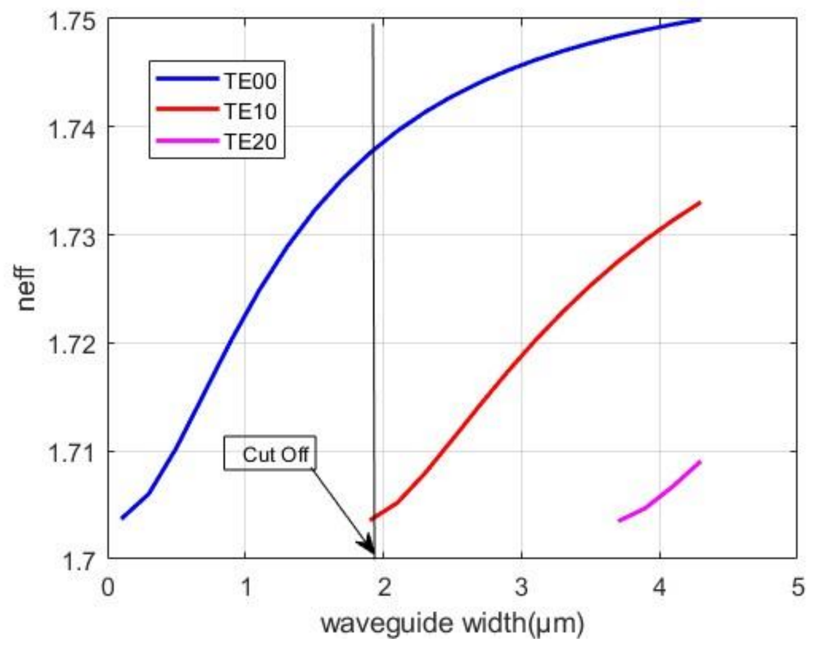
The Pockels effect describes how the refractive index of a crystal changes under the influence of an applied electric field

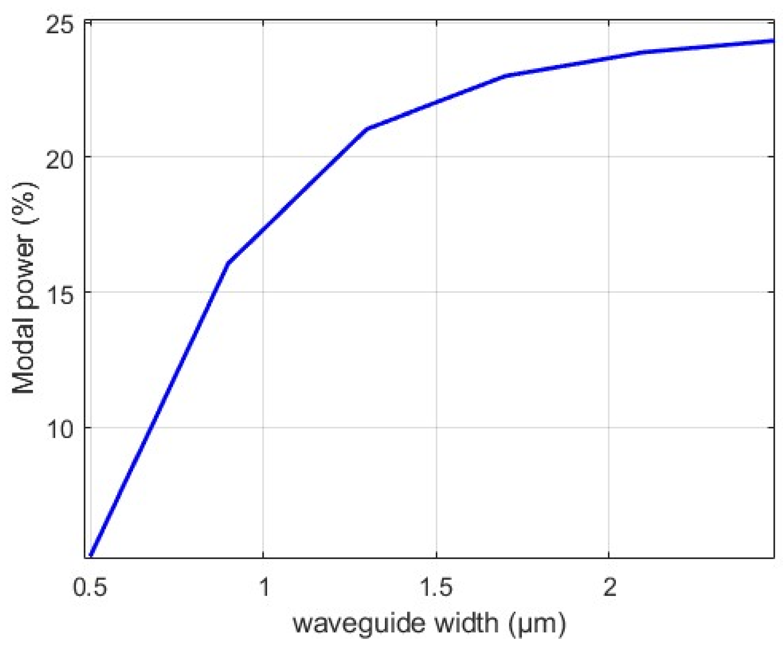
$$\Delta\left(\frac{1}{n_{ij}^2}\right)=\Delta(\varepsilon^{-1})_{ij}=\sum_{\gamma} r_{ij\gamma}E_{\gamma},$$

Here, n_{ij} is refractive index, $(\epsilon^{-1})_{ij}$ is the inverse of the electronic dielectric tensor, $r_{ij\gamma}$ the linear electro-optic tensor (EO tensor or Pockels tensor) and I, j, and γ stand for Cartesian coordinates

Simulated Model

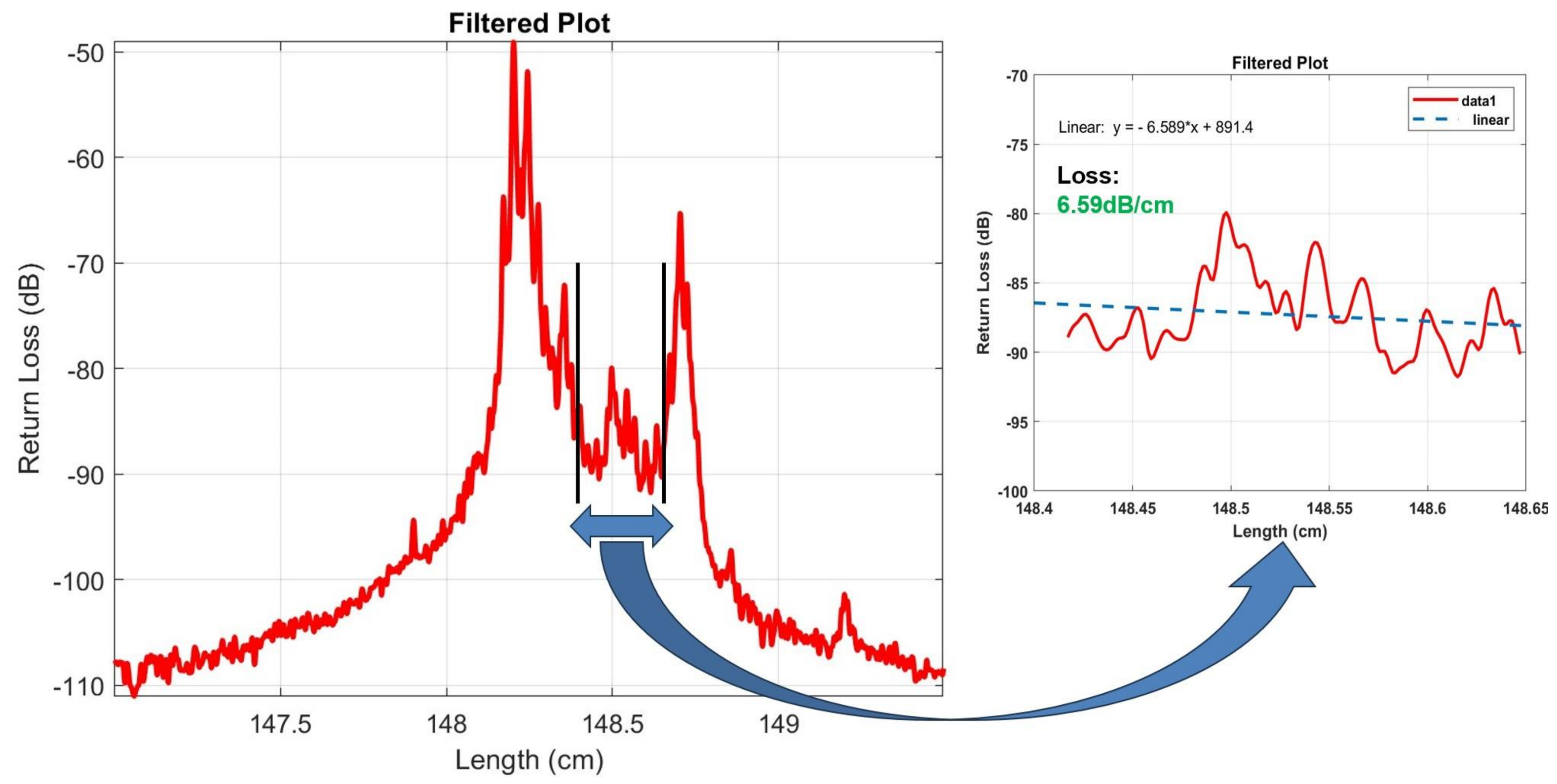






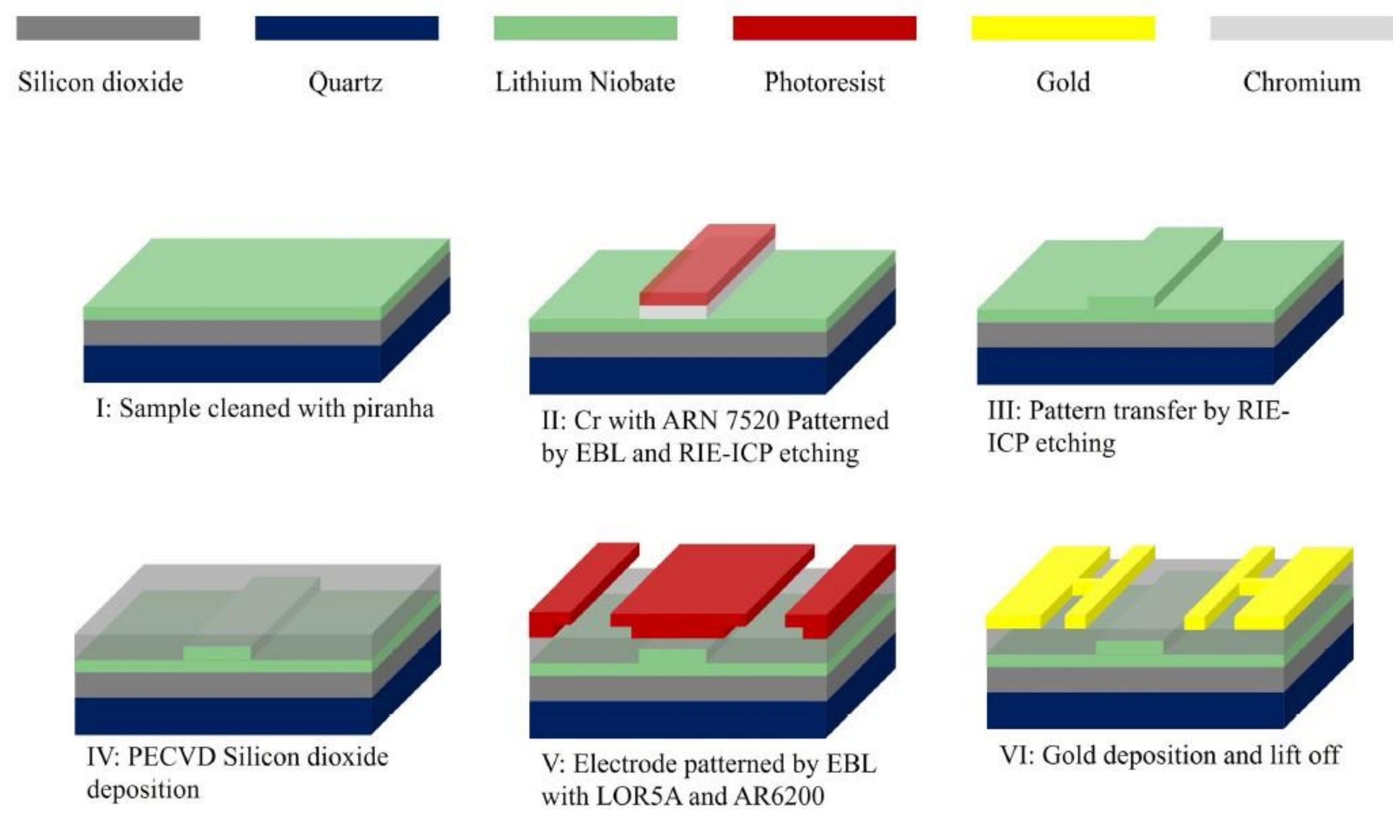
When it comes to the 'optical' part of the device, guiding of light can be achieved with strip-loaded waveguides and ridge-etched waveguides. The modal confinement is higher in the later, which can give rise to a better EO effect, but this may increase the propagation losses as the mode interacts more with the etched sidewall and its roughness.

Experimental Results



- Optical Back-scattering Reflectometer reveals propagation losses of BTO waveguides losses of the order 5.6dB/cm
- SEM images portray the smooth top and sidewall surfaces with decreased sidewall roughness owing to the optimized fabrication process

Fabrication



Conclusion and Future Work

- Poling of the ferroelectric domains is another significant study that needs to be conducted to activate the modulation effect for a BTO based EO modulator. The fabrication tolerance for several fabrication steps (EBL, Ion Beam Milling Etch) and the index matching of the optical and the RF components is still an unknown in the realm of BTO based optoelectronic devices which we look forward to figure out soon enough.

References

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2. Karvounis, Artemios, Flavia Timpu, Viola V. Vogler-Neuling, Romolo Savo, and Rachel Grange. "Barium titanate nanostructures and thin films for photonics." *Advanced Optical Materials* 8, no. 24 (2020): 2001249.