FRIEDRICH SCHILLER UNIVERSITÄT JENA
INSTITUTE OF APPLIED PHYSICS

Research Lab Work Project

by

Advisor

JENA

THESIS EVALUATION FORM

We certify that we have read this thesis and that in our opinion it is fully adequate, in scope and qualify as an master of science thesis in applied physics, based on the result of the oral examination taken place on ___/___/________

(ADVISOR)

(COMMITTEE MEMBER) (COMMITTEE MEMBER)

(CHAIRPERSON)

1. METHODS AND RESULTS

This section consists of the simulation physics which are utilized and simulation results of X-cut Z-cut EO modulators.

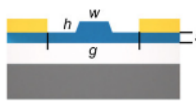
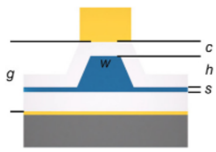
There are two simulation physics utilized one of them is to determine optical field mode in TFLN waveguide and it is called as *Electromagnetics Wave, Frequency Domain (ewfd)*. The other physic utilized is *Electrostatics (es)* to simulate static field distribution through gap area of CPW.

Firstly, simulation configurations are checked by realizing the geometry based on the paper [**?**]. The mode confinement and overlap with DC field distribution are derived from COMSOL 6.0. Then COMSOL-MATLAB Livelink is utilized in order to calculate overlap integral and V_π voltage is calculated based on that value. After than that, another simulation was run for the modulator which Girish Karthik experimentally measured in the laboratory and results are compared. Finally, parametric simulations are done to observe how $V_\pi L$ value responds to these changes and to see how loss can be limiting factor to realize some of the modulator geometries.

Verification of Simulation

Zhang et al. [**?**] has calculated V_π voltages for different thin film optical waveguides.

Table 1.1: X-cut and Z-cut TFLN modulator dimensions and calculated $V_\pi.L$ values by Zhang et al. [21]

Label	**X-Cut LN**	**Z-Cut LN**
Structure		
Slab thickness (s)	200 nm	300 nm
Ridge height (h)	400 nm	1.2 μm
Ridge width (w)	770 nm	800 nm
Cladding thickness (c)	Parametric	3.2 μm
Metal gap (g)	2μm	700 nm
$V_\pi.L$ (push-pull)	2.25 $V.cm$	2.6 $V.cm$

In their study, they focused on all-LN x-cut rib waveguide desing and all-LN z-cut rib waveguide design with planar electrode, which is in line with the aim of this work.

In the table ??, calculated $V_\pi.L$ values and corresponding dimensions are given. In this work, $V_\pi L$ product is calculated to verify the simulation physics used and parameter configurations.

Geometry	Mode Index	Overlap	$V_\pi L$
X-cut	1.8872	0.5230	2.1679V
Z-cut	2.029	0.3516	2.4117V

Table 1.2: Simulation results for X-cut and Z-cut Modulators

In table ??, the results of simulations, are done in this work, are seen. Mode index difference occurs due to different ridge height in two waveguide. As the ridge height decreases, wave will be more confined and the difference between mode index and material's refractive index increases. Also, large overlap value is result of having confinement in small region.

Table 1.3: $V_\pi L$ voltage comparision of this work with the ones obtained by Zhang et al. [?]

X-Cut Modulator		Z-cut Modulator	
This Work	Paper	This Work	Paper
2.1679 V.cm	2.25 V.cm	2.4117 V.cm	2.60 V.cm

Zhang et al. [?] has indicated that $V_\pi.L$ values in their paper are quantitative results for starting design of abovementioned geometries. This means values are not optimized. In the light of this information, percent error is calculated as 3.65% in X-cut modulator and 7.24% in Z-cut modulator.

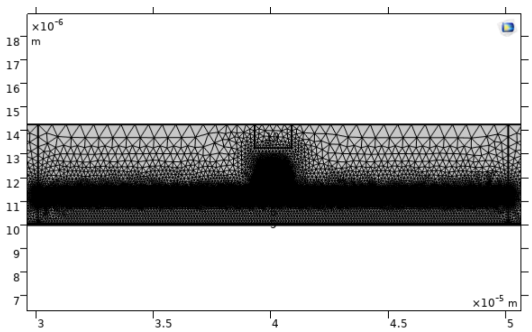


Figure 1.1: Optical mesh which COMSOL *EM Wave Frequency Domain (ewfd)* generates

In Figure ?? and ?? measured meshes are seen. In order to precisely solve the domains where field modes confine, polygon definition is made and the region inside that polygon has more precise mesh.

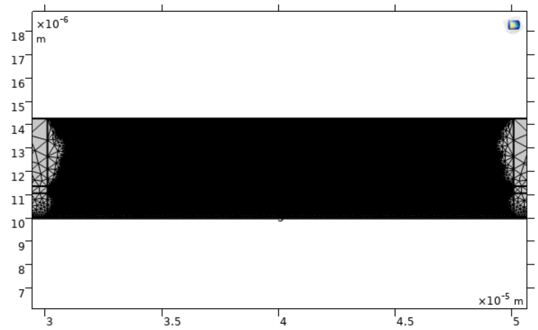


Figure 1.2: DC mesh which COMSOL *Electrostatic (es)* generates

Experimentally Verified V_π

Transmission characteristic of sample EO MZM is seen in Figure **??** and measurement process was carried out by Girish Karthik.

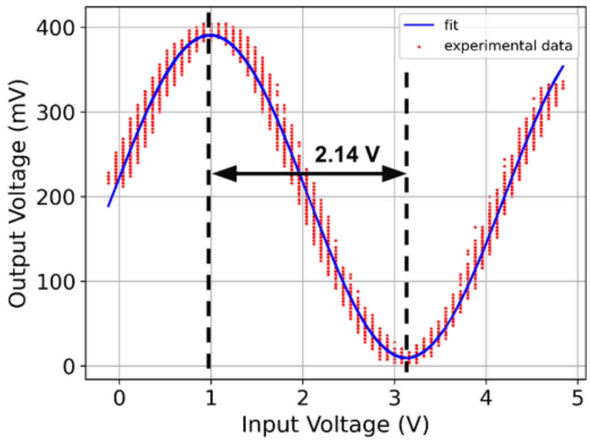


Figure 1.3: Transmission characteristic of sample modulator with length of 0.920cm. Red dots represents experimental data which is sampled by oscilloscope.

Since $V_\pi L$ voltage is constant and voltage and length of modulator is inversely propotional, 1-cm-modulator has smaller voltage value which is seen in Table **??**. Percent error between experimental and simulation data is 29.7%.

Method	Mode Index	Overlap	$V_\pi L$
Realized Measurement	-	-	1.969 V.cm
Simulation	1.9125	0.2598	2.8301 V.cm

Table 1.4: Experimentally measured $V_\pi L$ value and its simulation results

Parametric Sweep In X-cut Modulator - $V_{\pi}L$ And Top SiO_2 Layer Dependence

Thickness change of top layer silica has effect on the overlap integral. As the microwave electrodes moves away from optical waveguide, overlap integral decreases. This effect can be seen on the figure ??.

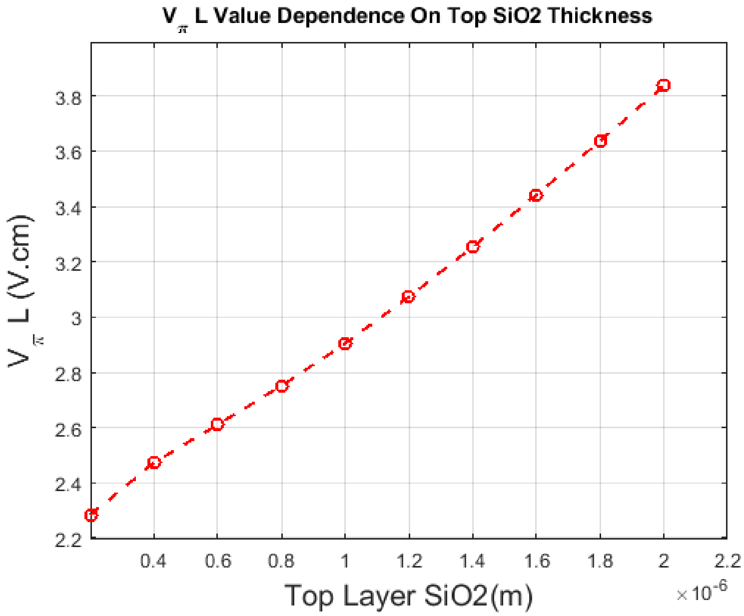


Figure 1.4: In x-cut EO MZM, top layer silica has changed and reduced

In order to have small V_{π} value, one can think to place the electrodes as close as possible to optical waveguide. However, plasmonic behavior start to arise in that case since metal-dielectric boundary becomes easily available for the optical wave and optical confinement is not achieved. This effect is seen in figure ??.

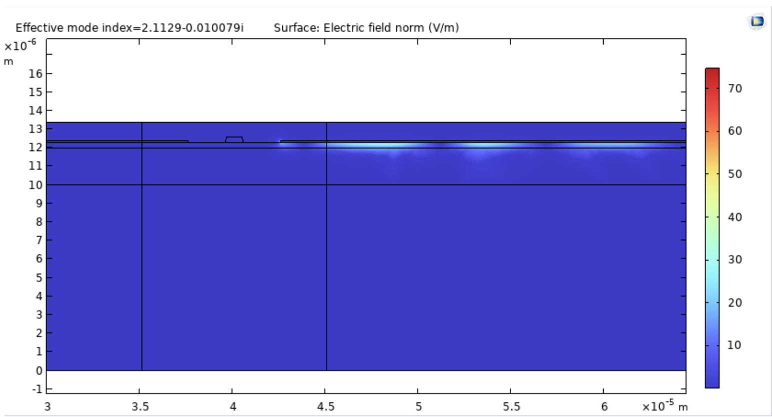


Figure 1.5: Plasmonic behavior in metal-LN interface. Silica layer is removed in this case.

The top silica layer helps preserve optical confinement and the overlap integral, preventing degradation that would otherwise increase optical loss

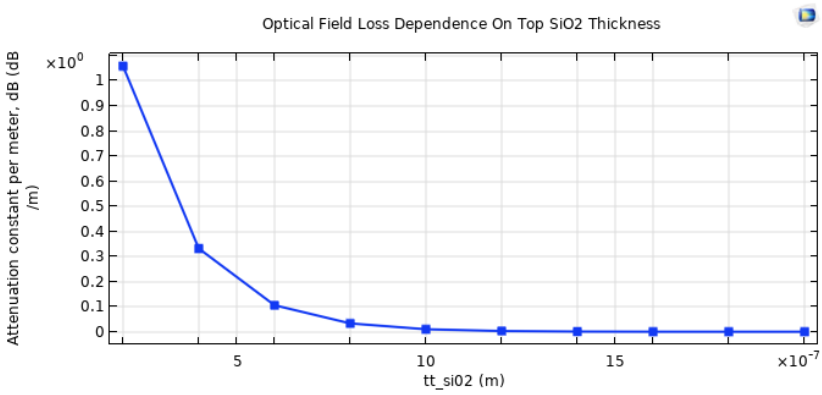


Figure 1.6: In x-cut EO MZM, top layer silica (x-axis) has parametrically changed and corresponding loss values are observed.

As it is seen on figure **??**, if the metalic electrodes are close to optical waveguide losses (dB/m) will increase. Critical observation would be the speed of change, it can be represented in linear scale, instead of logarithmic one. However, it is still undesirable.

Parametric Sweep In X-cut Modulator - $V_\pi L$ And Coplanar Waveguide Gap Dependence

Another approach to increase overlap between optical and microwave fields is having smaller gap between coplanar waveguide signal and ground electrodes.

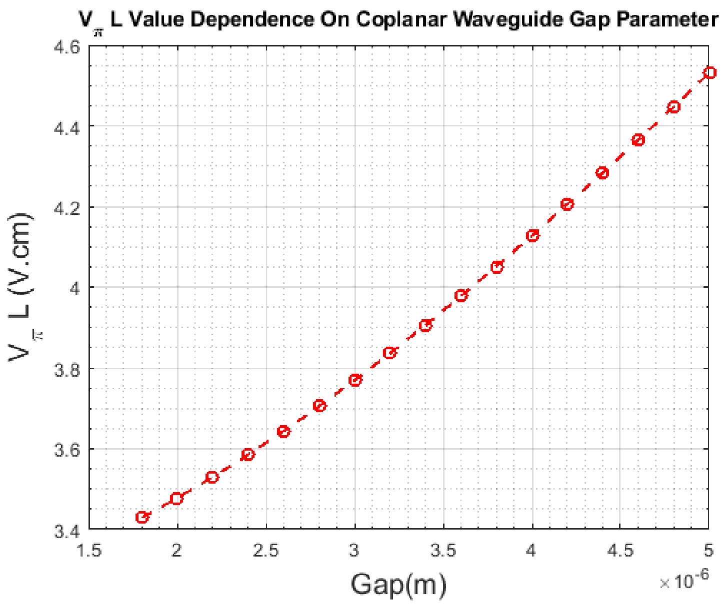


Figure 1.7: In x-cut EO MZM, gap between microwave electrodes has parametrically swept.

$V_\pi L$ value change almost linearly with respect to gap parameter in figure ??. Also, plasmonic effects still persist. This requires loss analysis for optical mode. In figure ??, change of loss in response to gap change is fast and small in amplitude. Increasing distance may decrease loss however it degrades V_π voltage.

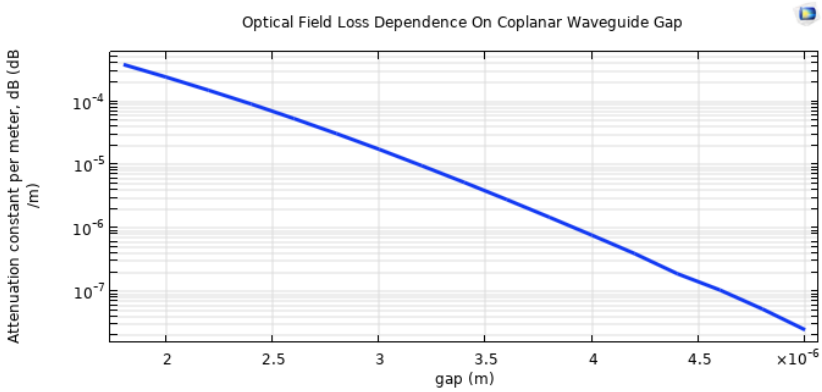


Figure 1.8: In x-cut EO MZM, change of gap and its effect on optical loss is seen. Vertical scale is logarithmic.

Parametric Sweep In Z-cut Modulator - $V_\pi L$ And Top SiO_2 Layer Dependence

Z-cut modulators have different microwave electrode orientation due to the reason mentioned in Optical Waveguides section. In this configuration top silica layer thickness has crucial effect on overlap integral and overall performance of the device.

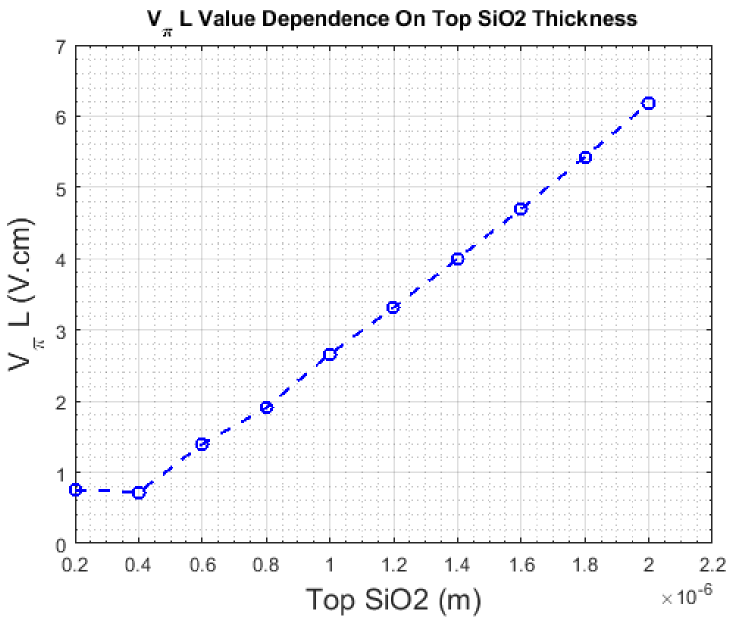


Figure 1.9: In z-cut EO MZM, change of top silica layer and $V_\pi L$ value relation is seen.

For a proper comparision, x-cut and z-cut modulators have both same top silica sweeps. However, z-cut modulator does not works properly for 200nm and 400nm top silica thicknesses because electrode overlaps with optical waveguide, which leads to unrealizable geometry. This result is seen in figure **??**. Considering $V_\pi L$ values starting from 600nm, they are almost linearly dependent on top silica thickness.

As for optical loss in z-cut modulator, it is drastically affected from top silica thickness. In figure **??**, vertical scale indicates loss (dB/m) and it is represented in logarithmic scale.

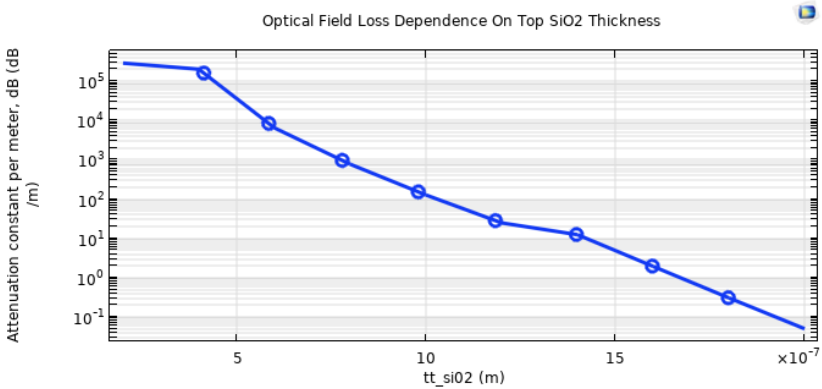


Figure 1.10: In z-cut EO MZM, change of top silica layer has strong impact on optical loss

For this large loss value, optical field does not confine in nonlinear medium, as in figure **??** and overlap integral degrades. Moreover, this unconfined mode supports the profitless $V_\pi L$ voltages for 200nm and 400nm in figure **??**.

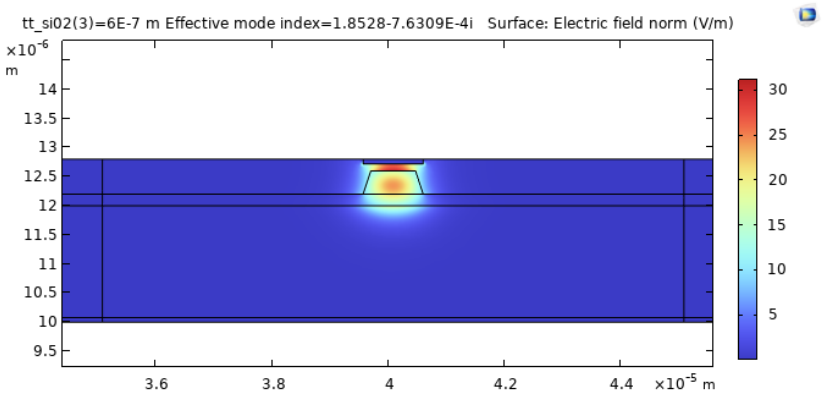


Figure 1.11: Due to severe loss, optical mode does not confine in z-cut modulator