# Novel structures for broadband electrooptic modulators in $LiNbO_3$

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***Abstract.*** *Real data of wet-etched ridge waveguide in Z-cut $LiNbO_3$ is combined with two new electrode structures to improve the performance of Mach-Zehnder electrooptic modulators. Calculations show improvements up to 50% in driving voltage in comparison with commercial and published devices in the 40GHz range. Simulation results and fabrication state is shown.*

## Introduction

External modulators based on lithium niobate ($LiNbO_3$) are being developed for high-speed and long-distance optical fiber transmission systems. Nowadays, they offer a modulation bandwidth exceeding 10 GHz combined with a low driving voltage, typically in the range of 5 V, with a voltage-length product ($V_\pi L$) in the order of 20 to 30 V·cm.

To enable higher bit rates and reduce the cost of modulator operation, lower voltages are required due to the restrictions of electrical instruments, in particular electrical driving amplifiers. Therefore, reduction of the driving voltage of a $LiNbO_3$ modulator is an extremely important issue for realizing future high-speed optical transmission systems. At the same time, the waveguide geometry and travelling-wave electrode structure must be optimized in order to reach high bandwidth performance and impedance matching.

Ridge waveguides in $LiNbO_3$ in combination with a proper geometric design of electrodes and dielectric buffer layer promise high bandwidth with low driving voltage [1-3]. Our proposed designs are based on real ridge waveguides made by Ti indiffusion in $LiNbO_3$ and wet etching techniques. They are evaluated regarding how the geometric design changes the main modulator parameters (overlap factor, effective index, characteristic impedance and frequency response). Also, fabrication possibilities are considered.

## Modeling of Mach-Zehnder modulators

In a Mach-Zehnder (MZ) type interferometric modulator, an applied electric field changes the refractive index, creating a phase shift between the waves propagating through both arms of the interferometer.

Z-cut $LiNbO_3$ together with travelling-wave Coplanar Waveguide (CPW) electrodes for the microwave (MW) modulating signal are used to create a push-pull effect in both arms, producing therefore an enhanced phase shift. A dielectric buffer layer is necessary to avoid absorption of the optical field in the metal surface.

The broadband electrode structure must be designed in such a way that the effective index of the CPW line matches the effective index of the optical waveguide and the electrode impedance is similar to that of the rest of the electronic drive circuit, usually 50 Ω. Furthermore, the overlap between optical and controlling MW fields must be optimized in order to get a low drive voltage.

With these objectives in mind, the characteristics of ridge Mach-Zehnder modulators were studied when two different electrode structures are used:
On one side, the CPW on ridge structure (figure 1, left) is the most direct way to use a traditional CPW electrode on a ridge. Nevertheless, the electrodes on the walls of the waveguides lead to a non-optimal use of the vertical component of the electric field and the different levels of the electrodes make more difficult the accurate fabrication of these devices. Therefore, the new Surface-Compact CPW (SCCPW) structure is proposed here, combining an alternative design of the CPW electrode together with ridge waveguides below the $LiNbO_3$ surface (figure 2, right).

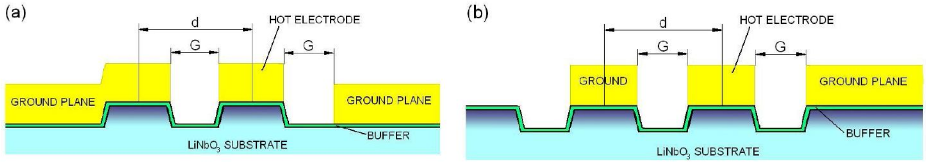


Figure 1: Cross section of the CPW structure on ridge (a) and the new proposed SCCPW (b).

The waveguide design was based on experimental results of wet-etched ridge waveguide fabrication on $LiNbO_3$ [4]. Mode profiles were simulated using a finite difference commercial software with Ti indiffusion index profiles calculated from the fabrication parameters [5]. Mode comparison with experimental results showed a good agreement.
The overlap integral for each waveguide ($\Gamma_i$) was calculated using own software.
From the electric capacitance of the structure, the electrode impedance ($Z$) and the microwave effective index ($n_{eff}^{MW}$) are also calculated.
In order to evaluate the transmission of the MW signal along the interaction length, the voltage signal at each $x$ point along the electrode in a time $t$ is taken as following:

$$V(x,t) = V_0\, 10^{\frac{-\alpha(f_{MW})L}{10}} \cos\left(\beta_{MW}x - \omega_{MW}t + \phi_0\right), \tag{1}$$

where $V_0$ is the applied voltage, $\beta_{MW}$ is the microwave propagation constant in the electrode, $\omega_{MW}$ is the microwave frequency, $\phi_0$ is the initial phase and $\alpha(f_{MW})$ is the frequency dependent microwave loss along the electrode calculated as $\alpha(f_{MW}) = \alpha_0\sqrt{f_{MW}}$, where 0.4 dB cm$^{-1}$ GHz$^{-1/2}$ is taken as usual value for $\alpha_0$. The modulated signal was evaluated after four reflections on the active length edges regarding to the impedance mismatch. Afterwards, the phase-shift is calculated taking into account the index mismatch between the optical wave and the modulating MW as:

$$\Delta\phi_i = \frac{\pi {n_{eff}^{op}}^3 r_{33}\Gamma_i}{\lambda G}\int_0^L V\left(\tilde{x}, t(\tilde{x})\right) d\tilde{x}, \tag{2}$$

where $i$ designates each one of the two parallel waveguides and the values $\tilde{x}$ are a dense set of points along the electrode length. The time is chosen as: $t(\tilde{x}) = \tilde{x}\, n_{eff}^{op}/c$. Finally, the total phase-shift ($\Delta\phi$) can be calculated as the sum of the phase-shifts from both waveguides. The optical response, $m$, of the modulator is defined by the equation:

$$m(f_{MW}) = \left|\frac{\Delta\phi(f_{MW})}{\Delta\phi(0)}\right|, \tag{3}$$

where $f_{MW}$ is the microwave frequency and $\Delta\phi(0)$ is the DC phase-shift.

## Modeling results

The presented calculation was applied to the structures shown in figure 1. Both structures are able to reduce the voltage-length product of the modulator by more than 50% of that of the traditional in-diffused waveguide modulators. Besides, the SCCPW gives even lower values of $V_\pi L$ than the CPW and improves velocity matching.

Waveguide separation of 9 μm was chosen as best trade-off between enhancement of electric field and optical mode separation [3].

In figure 2, the calculation of $V_\pi L$, $n_{eff}^{MW}$ and $Z$ is shown for the CPW on ridge and SCCPW as a function of the buffer layer thickness ($t_b$). One can see that the SCCPW reduces the $V_\pi L$ value by a 4%, allowing index matching with thinner buffer layer and improving impedance matching.

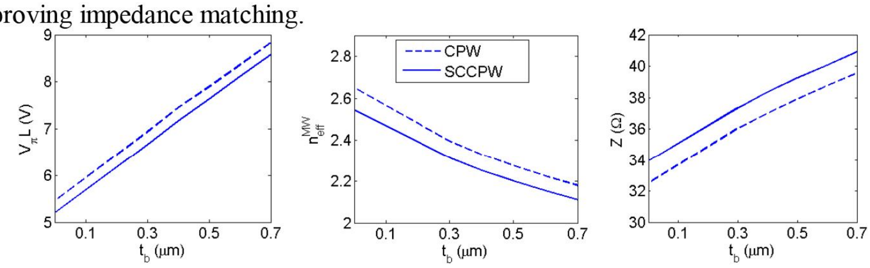


Figure 2: Calculation of the voltage-length product (left), microwave effective index (centre) and electrode characteristic impedance (right) for the CPW on ridge and the SCCPW structure.

In order to design devices with high performance, two different approaches where made. On one hand, it is important to find devices with high bandwidth and a driving voltage as reduced as possible. On the other hand, it is also interesting to find designs with lower bandwidth (say 10 GHz) but with drastically reduced driving voltage. With this aim, the calculations were focused on the SCCPW structure for two different active lengths: 25 and 50 mm, and analyzed with the buffer layer thickness as parameter. The $m$ and $V_\pi L$ obtained parameters are shown as a function of the modulating frequency in figure 3.

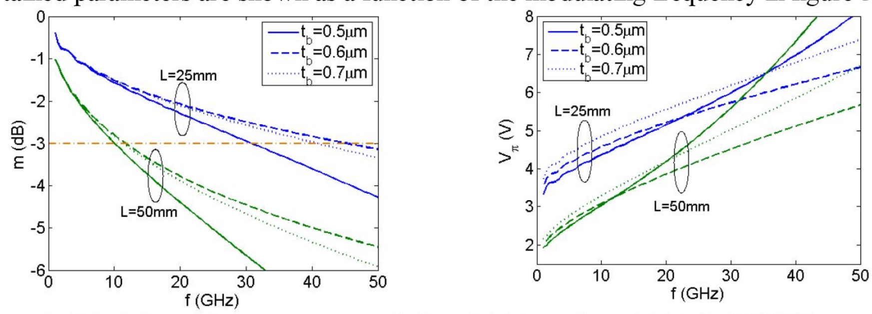


Figure 3: Calculation of frequency response (left) and driving voltage (right) for SCCPW structure as function of the modulating frequency for two active lengths. The buffer layer thickness ($t_b$) is used as a parameter.

In these figures, one sees how the 3dB optical bandwidth is maximum for $t_b$=0.6 μm, which accounts for the index matching between optical and MW signals. This is also evident in $V_\pi L$, where the value for $t_b$=0.6 μm is optimum for high frequencies.

Based on these results, two main designs can be proposed using the new SCCPW structure. On one hand, a broadband and low drive voltage device can be made with an active length of 25mm using a buffer layer of 0.6 μm thickness, providing a 3dB optical bandwidth of 45 GHz, and a voltage-length product of 8.11 V·cm, which gives a driving voltage of 3.24V for DC and 6.22V for 40GHz.

On the other hand, if the active length is 50mm, using a 0.5 μm thick buffer layer, we reach a 3dB optical bandwidth of 10GHz with a voltage-length product of 7.63V·cm and a driving voltage of 1.53V for DC and 3.03V for 10GHz.

Both designs use a distance between centers of waveguides of 18μm, waveguide width of 9μm and electrode thickness of 8 μm with a characteristic loss of 0.4dB $cm^{-1}$ $GHz^{-1/2}$.

## Fabrication

The fabrication of the SCCPW modulator is a challenging issue that is currently being carried out. Wet-etching in lithium niobate and microlithography techniques are adapted and applied to the fabrication of complete ridge structure and electrodes. Micrographs of fabricated parts of the devices can be seen in figure 4.

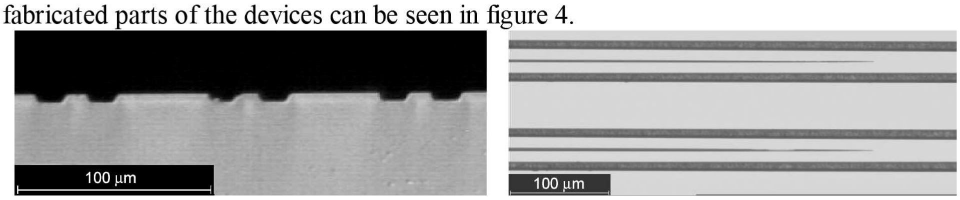


Figure 4: Fabricated end faces of the modulator ridge waveguides (left) and Y-splitters (right).

## Conclusions

Two novel structures for Mach-Zehnder electrooptic modulators in $LiNbO_3$ have been analyzed in depth. These designs are based on experimental results of waveguides fabricated by wet etching technique. Two specific designs were proposed for the new SCCPW structure. One of them is able to reach a bandwidth of 45GHz with a $V_\pi$(DC) of 3.24V and length of 25mm. The other one provides 10GHz bandwidth with $V_\pi$(DC) of 1.53V and a length of 50mm. The fabrication of these devices is currently in progress.

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