Thin-film lithium-niobate-on-insulator modulators at a wavelength of 1064nm for high-power applications

Hao Yan
Centre for Optical and Electromagnetic Research
State Key Laboratory for Modern Optical Instrumentation
Zhejiang University
Hangzhou, China
yanhao53@zju.edu.cn

Bingcheng Pan
Centre for Optical and Electromagnetic Research
State Key Laboratory for Modern Optical Instrumentation
Zhejiang University
Hangzhou, China
pbc@zju.edu.cn

Yiwei Xie
Centre for Optical and Electromagnetic Research
State Key Laboratory for Modern Optical Instrumentation
Zhejiang University
Hangzhou, China; *Advance Laser Technology Laboratory of Anhui Province*, Anhui, 230037, China
xieyiw@zju.edu.cn

Liu Liu
Centre for Optical and Electromagnetic Research
State Key Laboratory for Modern Optical Instrumentation
Zhejiang University
Hangzhou, China
liuliuopt@zju.edu.cn

Lai Zhi
School of optoelectronic engineering
Xidian University
Xian, China
zlai@mail.xidian.edu.cn

Daoxin Dai
Centre for Optical and Electromagnetic Research
State Key Laboratory for Modern Optical Instrumentation
Zhejiang University
Hangzhou, China
dxdai@zju.edu.cn

***Abstract*— Optical signals at 1064 nm have great applications in laser ranging, altimetry, and atmosphere remote sensing areas. However, electro-optic modulator at 1064 nm, as the key device for electro and optic signal conversion, has not been studied. Here we design a 1064 nm electro-optic modulator on the thin-film lithium niobate (LN) using two Mach-Zehnder interferometers connected in parallel. The fabricated device exhibits a voltage-length product of 1.92 V·cm and a 3-dB-bandwidth of around 5 GHz (theoretical > 120 GHz) which is limited by the photodetector available in the lab.**

Keywords-1064 nm wavelength; electro-optic modulator; thin-film lithium niobate

I. INTRODUCTION

Optical signals at 1064 nm wavelength are mainly used in the fields of space optical communication, pulse generation, frequency shift, optical fiber sensing, analog transmission and applications for high-power signal output thanks to the strong spectrum power at 1064 nm in lasers. Dual parallel Mach–Zehnder modulators (DP-MZMs) are the key components in most Radio over Fiber (RoF) systems because of their compact structure and many controllable parameters that can be used in double-sideband suppressed-carrier (DSSC), optical sing sideband with carrier (OSSB) and other advanced modulation formats [1]. However, most efforts of DP-MZMs design have been focused on infrared telecommunications wavelengths [2], with very little consideration for 1064 nm wavelength applications. As for the material to release DP-MZMs, Lithium niobate (LN) crystal has excellent characteristics such as wide transmission window, high non-linear coefficient, high refractive index and large electro-optical coefficient, and is an important candidate for substrate materials of photonic integrated devices**.** Compared with traditional Lithium niobate modulators based on crystalline LN, Lithium niobate-on-insulator (LNOI)–based LN electro-optic modulator features CMOS-compatible driving voltage, high integration and good signal fidelity, thus enabling high-performance electro-optic modulation with seamless integration to CMOS [3].

Here, we design a DP-MZM at a wavelength of 1064 nm on the thin-film LN platform. In order to avoid metal loss, the waveguide is coated in SU8 by UV lithography. The waveguide structure design is also optimized carefully for good working performance. Furthermore, the device is fully packaged, which makes the device more robust and easy operation in real applications. The fully-packaged device exhibits an on-chip loss of around 5 dB, a voltage-length product of 1.92V·cm for a 3-mm long device, and an EO bandwidth of more than 5 GHz (limited by the bandwidth of the photodetector used in the experiment). The present DPMZM is promising to play a key role in 1064-nm-wavelength optical systems.

II. DEVICE STRUCTURE

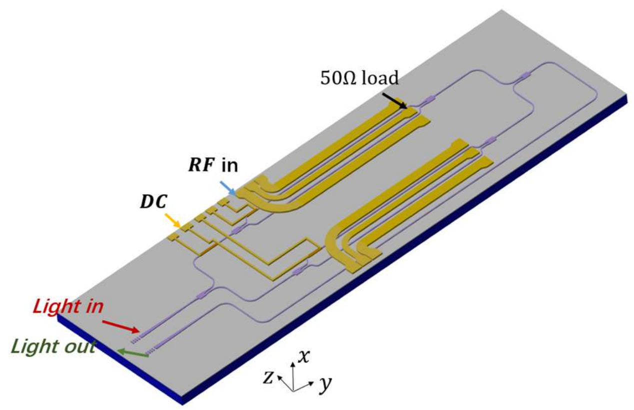

Figure 1. 3D structure of the proposed DPMZI near infrared modulator in LNOI.

Figure 1 the three-dimensional (3D) structure of the proposed light DP-MZM at wavelength of 1064nm in LNOI. Considering the easy of optical packaging, we use grating coupler array to receive carrier wave and output modulated signal. It is necessary to lead the RF electrode and heating electrode to the edge of the chip with metal for electrical packaging and wrap the waveguide in SU8 to avoid metal loss. The DP-MZM is mainly composed of a coupled grating array, 3-dB multimode interference coupler (MMI), thermal phase shifter to control offset work-point and two traveling wave modulation regions.

For light at 1.064 μm travelling in x-z plane on an x-cut 300-nm LNOI waveguide, the effective refractive indices of the TE0 (solid) and TE1 (dashed) modes are calculated as a function of the top width *w* when choosing different rib heights *h*, as shown in Figure 2(a). To satisfy the single-mode condition and resolution requirement of fabrication [4], top width *w* is chosen as 0.8 μm, while the rib height h is 150nm. The 3-dB coupler used in the MZI is realized by a MMI coupler, as shown in Figure 2(b). The parameters of the MMI is $L_{\mathrm{mmi}} = 26$ μm , $W_{\mathrm{mmi}} = 5$μm , $W_{\mathrm{taper}} = 1.6$μm and $L_{\mathrm{taper}} = 10$μm . Figure 2(c) plots the simulated transmission at the upper-(blue) and lower-(red) ports, respectively, indicating uniform and low-loss power splitting in a wideband spectrum. The peak coupling efficiency is 49.7% at 1064 nm. Because of the symmetry of the device, the output performance in the other output port is the same. The inset shows the simulated light propagation |E| in the designed MMI coupler with the TE0 mode input at 1.064 μm.

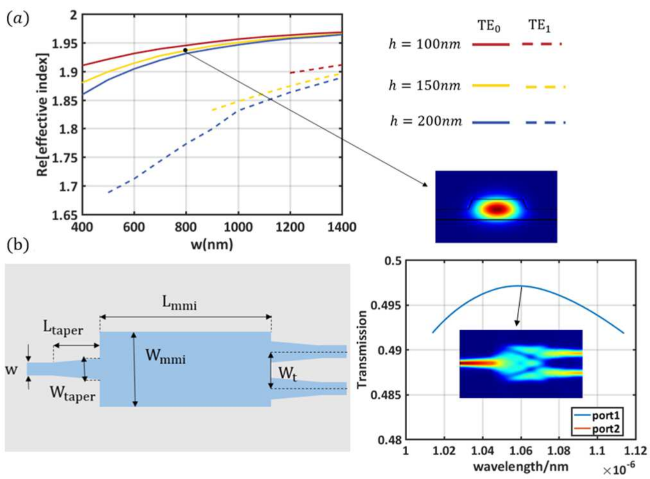

Figure 2. (a) Calculated effective refractive indices for the TE0 (solid) and TE1 (dashed) modes in x-z plane waveguide of x-cut 600-nm LNOI platform at different rib heights h and top widths w. (Inset : simulated field profile of TE_0 mode). (b) The top view schematic of the 3-dB MMI coupler. (c) Calculated two-port transmissions of the designed MMI splitter for the TE0-mode input, inset: simulated light propagation in the designed MMI at 1.064 μm.

The characteristics of a traveling wave MZI modulator are mainly determined by the cross-section of the modulation section [5], which is labeled and shown in Figure 3(a). The structural parameters of this cross-section are optimized first using a multiphysics model based on a finite element algorithm. Au with a thickness of 0.5 μm is used here as the electrode, which ensures a low microwave loss. The gap width g is chosen to be 4 μm to consider need of low $V_\pi L$ and the resolution requirement of UV lithography. The other parameters of the electrodes are designed $\mathrm{w_s} = 18$μm and $w_{\mathrm{g}} = 50$ μm. The width $\mathrm{w_0}$ and height h_0 of the SU8 strip cladding are 2.6 μm and 1μm respectively to. Figure 3(b) shows the simulated TE0 mode in the modulated LNOI waveguides as well as the electric field for a given voltage. The calculated impedance Re[Z0] of the designed electrodes is shown in Figure 3(c). Figure 3(d) shows the calculated effective index $\mathrm{n_m}$ of the RF mode which have the good velocity matching with optical mode whose group index is 2.374 (see the red dashed line). Figure 3(e) shows the calculated RF attenuation α_{m}, which is less than 9 dB/cm in the range of <60 GHz. In theory, according to the calculation formula of the overall modulation frequency response m[ω] of a travelling wave modulator [7], Figure 3(f). shows the calculated modulation response m[ω] of the designed modulator. It can be seen that the theoretical 3-dB EO bandwidth far exceeds 100 GHz.

Driven with the push-pull configuration, the voltage-length product is given as $V_\pi L = \mathrm{V}\lambda_0/(4\Delta_{\mathrm{neff}})$, where Δ_{neff} is the effective refractive index change of the fundamental TE mode with and without the applied voltage V [6]. In our calculation, the $V_\pi L$ is 1.57 V·cm. For the fabricated modulator, the arm-length for phase-shifting is 3 mm.

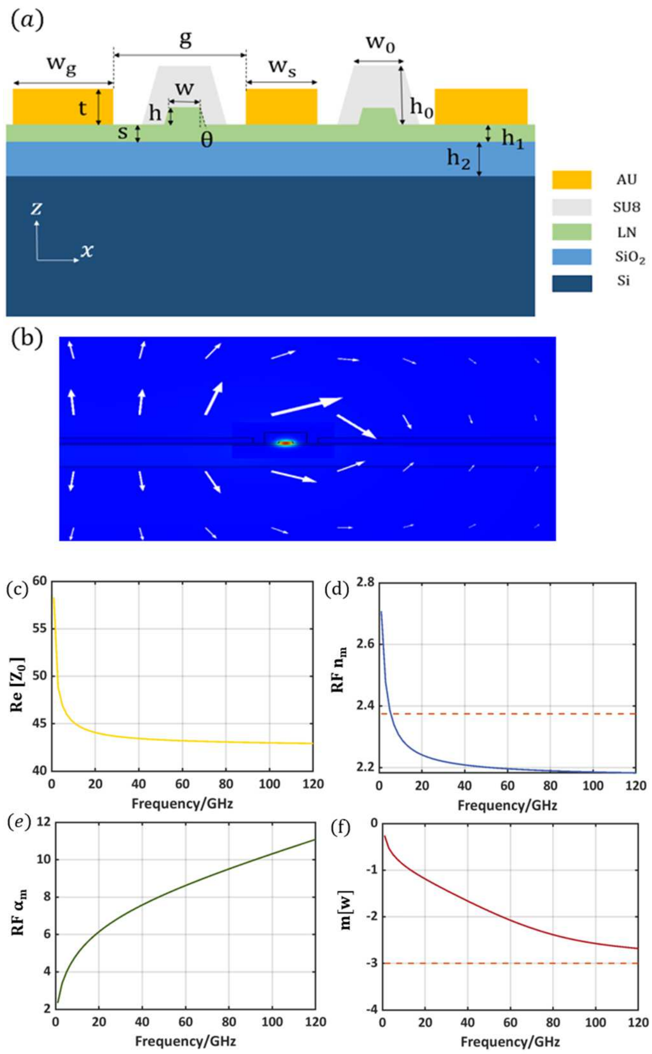

Figure 3. (a) Cross-section of the LNOI waveguides in the modulation region. (b)Simulated mode profile |E| of the TE0 mode (colored) and electric field distribution (inset: the RF field profile at the frequency of f = 100 GHz). Calculated results for the RF properties: (c) Impedance Re[Z0]; (d) RF

effective index n_m; (e) RF attenuation α_m; and (f) Calculated modulation response m[ω] of the designed modulator.

III. Fabrication and Result

The designed modulators were fabricated with a commercial x-cut LNOI wafer, in which a 300-nm LN thin film is bonded on top of a 2-μm-thick silica layer and a 0.8-mm-thick Si substrate. The grating coupler and waveguide patterns are defined by the electron beam lithography system (Rail Voyager), and 200 nm thick lithium niobate is etched by the inductively coupled plasma reactive ion etching (ICP-RIE) process. The fabrication processes were developed optimized carefully for achieving low-loss LNOI waveguides. Next, SU8 waveguide cladding structures were patterned using ultra-violet contact lithography. Then, the travelling electrode and heater made of gold and titanium was fabricated using lift-off processes. Figure 4(a) shows the optical microscope image of our fabricated DP-MZMs, with the enlarged images of the power splitter. Figure 4(b) shows the schematic of the experimental setup. In the experiment, the RF signal was applied to the travelling-wave electrodes through a 40-GHz bandwidth RF probe (GGB 40A) and the RF signal after transmitting the device is terminated by attaching a second RF probe (GGB 40A) connected with a 50 Ω terminator to the electrodes. In our experiment the high-speed modulated signal was then received by a 1.064-μm photodetector with a bandwidth of around 5 GHz. The result given in Figure 4(c) was measured S_{21} parameter of the travelling-wave modulator from the vector network analyzer (VNA). Note that the photodetector response which is limited by the 5 GHz response bandwidth of the photodetector available in the lab. The measured half-wave voltage V_π is 6 V. The corresponding voltage–length product is $V_\pi L$ = 1.92 V·cm, which is close to the theoretical value of 1.59 V·cm. The difference between the measured $V\pi L$ and the theoretical result is partially due to some errors in the testing and the fabrication (e.g., the metal strips were widened due to the UV lithography). The insertion loss of the device is about 5dB.

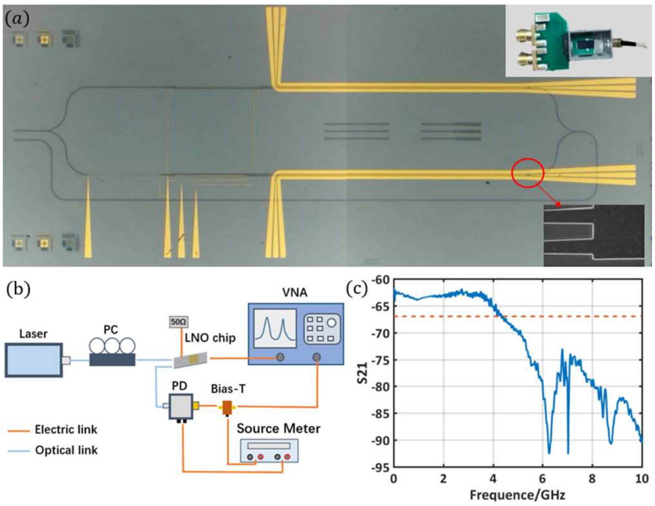

Figure 4. (a) Optical microscope images of the fabricated DP-MZM with an SEM image of a power splitter. Inset: Photograph of the Packaged chip. (b) Schematic of the experimental setup; (c) Measured S_{21} of the travelling-wave electrodes.

.

IV. Conclusion

In conclusion, we have demonstrated a DP-MZM working at the 1064 nm wavelength-band by using the LNOI platform. The presented modulator uses two Mach–Zehnder modulators (MZMs) connected in parallel which can be used for special modulation formats. The simulated low voltage-length product of 1.57 V·cm and a 3-dB-bandwidth of >120 GHz at a length of 3 mm. The presented device exhibits a voltage-length product of 1.92V·cm, and an EO bandwidth of more than 5 GHz (which is limited by the photodetector) and insertion loss of about 5dB. Such an optimized EO modulator at 1064 nm is believed to play a key role in the applications of space optical communication, pulse generation, frequency shift, optical fiber sensing, analog transmission and applications for high-power signal output.

Acknowledgment

This work was supported by Zhejiang Provincial Natural Science Foundation (LGF21F050003); National Natural Science Foundation of China (NSFC) (62175214, 61905209, 62111530147); Open Project of Advanced Laser Technology Laboratory of Anhui Province (AHL2021KF05).

References

[1] C . Wang, M. Zhang, X. Chen, et al. Integrated lithium niobate electro-optic modulators operating at CMOS-compatible voltages, Nature, 562:101–4, 2018.

[2] Z. Wang, G. Chen, Z. Ruan, R. Gan, P. Huang, Z. Zheng, L. Liu, Silicon–Lithium Niobate Hybrid Intensity and Coherent Modulators Using a Periodic Capacitively Loaded Traveling-Wave Electrode, ACS Photonics, 2022.

[3] Y. Qi, Y. Li, Integrated lithium niobate photonics, Nanophotonics, vol. 9, no. 6, pp.1287-1320, 2020.

[4] G. Zhu, W. Liu and H. R. Fetterman, A Broadband Linearized Coherent Analog Fiber-Optic Link Employing Dual Parallel Mach–Zehnder Modulators, IEEE Photonics Technology Letters, vol. 21, no. 21, pp. 1627-1629, 2009.

[5] B. Pan, J. Hu, Y. Huang, L. Song, J. Wang, P. Chen, Z. Yu, L. Liu, and D. Dai, Demonstration of high-speed thin-film lithium-niobate-on-insulator optical modulators at the 2-μm wavelength, Opt. Express 29, 17710-17717, 2021.

[6] M. He, M. Xu, Y. Ren, J. Jian, Z. Ruan, Y. Xu, *et al.*, High-performance hybrid silicon and lithium niobate Mach–Zehnder modulators for 100 Gbit s−1 and beyond. Nat. Photonics 13, 359–364, 2019.

[7] C. Li, P. Chen, J. Li, K. Chen, C. Guo, L. Liu, Modeling of thin-film lithium niobate modulator for visible light, Opt. Eng. 61(5), 057101, 2022.

[8] G. Ghione, Semiconductor devices for high-speed optoelectronics, Oxford University, 2009.