Low-Voltage Electro-Optic Modulator Structure using Transparent Conducting Oxide with High Conductivity-Loss Ratio as Electrodes

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Abstract: We describe a novel design of electro-optical modulator using transparent conducting oxide (TCO) with high σ/α ratio as electrode. We show that by engineering TCO's σ/α ratio, both low voltage and high-speed can be achieved.

1. INTRODUCTION

Recently there has been much interest in reducing the switching voltage of electro-optic (EO) modulator to <1V for RF photonics applications [1,2]. One way to reduce the modulation voltage is to increase the material EO coefficient and various new organic and inorganic materials with higher EO coefficients have been developed [2-4]. Another way is to reduce the electrode spacing. However, metallic electrodes have high optical absorption loss, limiting how small electrode spacing can be. Recently, there has been much development of novel transparent conducting oxide materials, some of which such as Cadmium Oxide (CdO) has been reported to have low optical loss at 1550nm wavelength range [5]. The more familiar Indium Tin Oxide (ITO) is only one example within a large class of TCO materials. It is thus of interest to explore the appropriate use of TCO materials to optimally reduce the switching voltage of modulators and yet still maintain high modulation frequency. In this paper we will focus on a novel side-injection electrode structure that is particularly conducive for organic EO materials with low refractive index. We will discuss the TCO material properties needed to achieve the desired low voltage and high speed performances.

2. TCO ELECTRODE MODULATOR STRUCTURE

Conventional modulator utilizes metals as electrode. For example, in the case of a top-down electrode configuration, to avoid the metal contact induced optical loss in the optical waveguide (WG), the top and bottom WG cladding usually has to be thicker than a few microns to eliminate the metal loss. For example, an exemplary self-assembled-superlattice (SAS) organic EO modulator structure [2] has top and bottom cladding thickness larger than 2.0µm and 2.5 µm, respectively, to reduce the metal loss to <0.1/cm. The thick cladding increases the applied switching voltage of the modulator by 4x compared to if the electrodes are just across the WG core. The voltage drop across the cladding layers can be eliminated by placing TCO electrodes directly across the EO material.

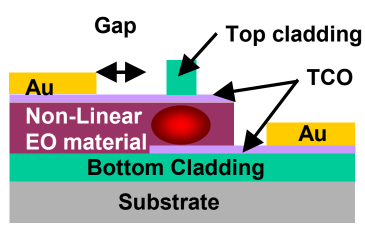

Fig. 1. Structure of TCO modulator with side injection configuration.

For such applications, side injection modulator structure is proposed, as shown in **Fig. 1**. In this case, the TCO is thin (tens to hundreds of nm) and form part of the core, while the top and bottom claddings are formed by the usual lower-refractive-index dielectric materials. As shown below, for modulator applications, high modulation speed requires a high TCO material conductivity σ while low optical loss requires a low absorption coefficient α. Hence, a high σ to α ratio will lead to high speed-voltage performances, making the value of σ/α as an essential TCO's materials Figure of Merit for modulator applications.

3. MODULATOR HIGH-SPEED RF TRANSMISSION LINE DESIGN

In this section we will discuss an appropriate RF transmission line model for the TCO based modulator and focus on the TCO conductivity needed to achieve operating speed above 20GHz. **Fig. 2** shows the equivalent circuit of traveling-wave EO modulator with TCO as electrodes. The TCO is modeled as a series resistor R_s. R_{con} is the metal transmission line conductor resistance; Lm is metal inductance; Cp is parasitic capacitance; Cm is capacitance of

modulator. Using the circuit parameters in **Fig. 2**, all of the relevant microwave properties of a traveling wave TCO EO modulator can be derived from [6,7]:
By including multiple microwave reflections inside the modulator [7], RF voltage can be expressed as:

$$V_{RF} = \frac{V_0 T \exp(j\omega t)}{1 - \Gamma_L \Gamma_S \exp(-2\gamma_\mu L)} \left[\exp(-\gamma_\mu x) + \Gamma_L \exp(\gamma_\mu x - 2 - \gamma_\mu L) \right], \tag{1}$$

The effective voltage drop along the modulator with electrode length L is:

$$V_{eff} = \frac{1}{L} \int_0^L \frac{1/j\omega C_m}{R_s + 1/j\omega C_m} V_{RF}\left(x, t = t_0 + \frac{x}{v_0} \right) dx, \tag{2}$$

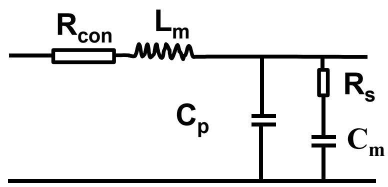

Fig. 2. Equivalent circuit of traveling-wave EO modulator.

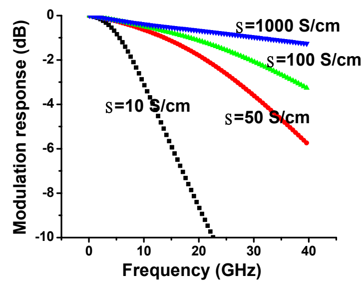

Fig. 3. Dependence of modulation bandwidth on conductivity of TCO.

In a numerical simulation, we assume the thickness of TCO layer on both sides of the WG core (**Fig. 1**) to be 50nm and the top and bottom claddings are Cytop and SiO_2, respectively. For this structure, the optical energy overlapping factor with the thin TCO layers is 1%. The device length is assumed to be 0.5cm with EO coefficient r_{ij}=60 pm/V and $\Gamma_{optical}$=80%. EO layer thickness is 1.5 μm with refractive index of 1.56. So the static π phase-shift switching voltage is 1V with pull-push configuration. **Fig. 3** shows the dependence of modulation bandwidth vs. conductivity of TCO. We see that with TCO conductivity σ>50 S/cm, the TCO modulator can operate above 20GHz. This give a σ/α figure-of-merit needed for the TCO material to be 50/45~1 S, which is achievable with some of the current TCO materials. Higher EO coefficient material will require even lower σ/α since the device can be made shorter.

4. CONCLUSION

We have described a new electro-optical modulator structure using transparent conducting oxide (TCO) as electrode. With this new structure, the switching voltage can potentially be reduced by 3-4 times compared to conventional modulator structure, and still maintain reasonably high modulation speed of >20GHz.

5. ACKNOWLEDGEMENT

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[1] N. Dagli, “Wide-Bandwidth Lasers and Modulators for RF Photonics”, Microwave Theory and Tech., 47, 1151, 1999.
[2] Z. Liu, S. T. Ho, S. S. Chang, and T. J. Marks, "Waveguide Electro-Optic Modulator Based on Organic Self-Assembled Superlattice (SAS)," 2002 Conference on Lasers and Electro-Optic, 73, 196, 2002.
[3] P. Zhu, van der Boom ME, H. Kang, G. Evmenenko, P. Dutta,T. Marks “Realization of expeditious layer-by-layer siloxane-based self-assembly as an efficient route to structurally regular acentric superlattices with large electro-optic responses”,Chem. Mater. 14, 4982, 2002
[4] M. Oh, H. Zhang, C. Zhang, H. Erlig, Y. Chang, B. Tsap, D. Chang, A. Szep, W. Sterier, H. Fetterman, L. Dalton, “Recent advances in electrooptical polymer modulators incorporating highly nonlinear chromophore”, IEEE J. Select. Topics Quantum Electron, 7, 826, 2001.
[5] A.J. Freeman, K.R. Poeppelmeier, T. O. Manson, R.P.H. Chang, and T.J. Marks, “Chemical and thin-film strategies for new transparent conducting oxides”, MRS Bulletin, Vol. 25, 45-51, 2000.
[6] Fawwaz T. Ulaby, “Fundamentals of applied electromagnetics”, Prentice Hall, 1999
[7] G.L. Li, C. K. Sun, S. A. Pappert, W. X. Chen, and P.K.L. Yu, “Ultrahigh-speed traveling-wave electroabsorption modulator-design and analysis”, IEEE Trans. Microwave Theory and Tech. 47, 1177, 1999.