Accepted Manuscript

A Deterministic Guide for Material and Mode Dependence of On-Chip Electro-Optic Modulator Performance

Rubab Amin, Can Suer, Zhizhen Ma, Ibrahim Sarpkaya, Jacob B. Khurgin, Ritesh Agarwal, Volker J. Sorger

PII: S0038-1101(17)30427-6
DOI: http://dx.doi.org/10.1016/j.sse.2017.06.024
Reference: SSE 7261

To appear in: *Solid-State Electronics*

Received Date: 27 May 2017
Accepted Date: 19 June 2017

A Deterministic Guide for Material and Mode Dependence of On-Chip Electro-Optic Modulator Performance

Rubab Amin[1], Can Suer[1], Zhizhen Ma[1], Ibrahim Sarpkaya[1],
Jacob B. Khurgin[2], Ritesh Agarwal[3], Volker J. Sorger[1,]*

[1]*Department of Electrical and Computer Engineering, George Washington University*
800 22nd St., Science & Engineering Hall, Washington, DC 20052, USA
[2]*Department of Electrical and Computer Engineering, Johns Hopkins University, Baltimore, Maryland 21218*
[3]*Department of Materials Science and Engineering, University of Pennsylvania, Philadelphia, PA 19104, USA*
**Corresponding Author: E-mail: sorger@gwu.edu*

Abstract
Electro-optic modulation is a key function in optical data communication and possible future optical computing engines. The performance of modulators intricately depends on the interaction between the actively modulated material and the propagating waveguide mode. While high-performing modulators were demonstrated before, the approaches were taken as ad-hoc. Here we show the first systematic investigation to incorporate a holistic analysis for high-performance and ultra-compact electro-optic modulators on-chip. We show that intricate interplay between active modulation material and optical mode plays a key role in the device operation. Based on physical tradeoffs such as index modulation, loss, optical confinement factors and slow-light effects, we find that bias-material-mode regions exist where high phase modulation and high loss (absorption) modulation is found. This work paves the way for a holistic design rule of electro-optic modulators for on-chip integration.

1. Introduction
The field of integrated optoelectronics offers potential information processing advantages for performance advances for both computing and information technology (IT). The inherently weak interaction of light and matter, however, introduces fundamental size (footprint), speed, and power (S^2P) limits to photonic-based information processing technologies. With signal modulation being fundamental for communication and computing applications, the search for high-performing S^2P modulators bears both scientific novelty and technological relevance. Here the focus is on electrical control of optical modulation, or short the electro-optic (EO) conversion, since it allows synergistic interfacing with electrical driver circuitry [1,2]. In terms of terminology, EO modulation is achieved by either changing the real part (n) of the modal refractive index leading to phase shifting-based interferometer-like devices termed electro-optic modulators (EOM), or by modulating the imaginary part (κ) of the modal index of linear electro-absorptive modulators (EAM). In both types, the fundamental complex index of refraction is altered electrically in the active material, which in turn modifies the propagation constant of the mode inside the respective waveguide. EOMs operate by changing the real part of the index, which relates to the phase of the light, whereas EAMs operate by changing the imaginary part of the index, which relates to the intensity absorption of the light. Another classification of modulators is the physical mechanism to introduce the index change; here two classifications divide EO modulators into either being driven by an electrical current, or driven by voltage (e.g. electric field). Their relative performance is essentially similar, except that the voltage-driven device requires sharp atomic resonances in order to be energy-efficient. However, since energy levels of any 2 level system is broadened within kT (k = Boltzmann constant, T = temperature), operation at room temperature slightly disadvantages voltage-driven modulators over current-driven counterparts. Thus, in this work we focus on current-driven mechanisms only.

The challenge for EOMs is fundamental; Kramers–Kronig relations dictate that changing the real part of the complex index independent from simultaneously altering the imaginary part is impossible. That is, for EOMs any increased loss in modulation is simply parasitic for the insertion loss (defined at the light ON state). In contrast, EAMs are not effected significantly by a change in the real-part of refractive index, upon tuning the loss. Thus, the index tuning-to-loss ratio is a fundamental figure-of-merit (FOM) for phase shifting modulators. Conventional electro-optic materials such as Silicon operating either with the plasma-dispersive carrier or Kerr effect show a rather low index change (Fig. 1a) [3-5]. The use of plasmonic modes has introduced the opportunity to shrink the active material from hundred's of nanometers (i.e. bulk modes) of Silicon or $LiNbO_3$ down to ten's of nanometers, while inserting the active material into the high field [6]. Similar to Silicon, transparent conducting oxides (TCOs), such as Indium Tin Oxide (ITO), are able to tune their index via the carrier-dependent Drude model (i.e. current-driven modulators). However, unlike Silicon the carrier concentration of ITO can be a) higher and b) more dramatically tuned compared to Silicon (Fig. 1c,d). This is due to a) the higher bandgap of ITO compared to that of Silicon, b) the presence of an epsilon-near-zero (ENZ) region in the allowed carrier concentration range, and c) the dependency of corresponding Drude model; the higher bandgap allows the density