Abstract

Densely integrated and energy-efficient photonics supporting high-speed data transmission is the need for the next-generation on-chip communication network. The mature silicon photonics technology has enabled the development of cost-effective and scalable photonic devices. However, their lack of strong electro-optical response and poor light-matter interaction (LMI) leads to inadequate performances at higher chip scaling owing to their sizeable device footprint. The future integrated circuit demands electro-optical modulator to be compact, energy-efficient, and exhibit ultra-fast broadband operation. It has stimulated the search for CMOS-compatible active material and device engineering with enhanced light and active material interaction. In this thesis, novel active materials facilitating strong bias-controlled index modulation such as Graphene and Indium tin oxide (ITO) are integrated with photonic and plasmonic configurations to develop high-performance on-chip integrated optical modulators. ITO serves as potential active material due to its strong electro-optical tunability in near-infrared regimes. A compact, broadband hybrid plasmonic modulator architecture was developed on low-loss silicon nitride platform by utilizing the epsilon near zero (ENZ) effect of electrostatically gated ITO to boost the electro-optical response. Numerical simulation reveals many orders of bandwidth improvement due to low sheet resistance offered by fabricated ITO, which reduced the overall RC circuit's series resistance. The synergy between the silicon nitride platform and hybrid plasmonic modulator driven by an ENZ ITO capacitor gave an extinction ratio of 6.48 dB at a compact size of 5.5 µm and modulation bandwidth of 12.84 GHz. Next, Graphene assisted electroabsorption modulator designs with enhanced LMI are proposed to minimize the switching energy to below 10 fJ/bit while retaining high modulation bandwidth ($>$ 10 GHz) for on-chip optical communication. The modulation efficiency is strengthened with increased overlap between Graphene and the guided optical mode along with large orientation match between confined field polarization and Graphene plane. We obtained a high figure of merit of 7.98 defined by large bandwidth and low switching energy. Integrating double-layer Graphene into asymmetric vertical slot configuration offered ten times improvement in the figure of merit with sub-femtojoule switching energy and high modulation bandwidth of 72 GHz. However, the footprint of the waveguide integrated Graphene based modulator is still large. A Graphene integrated asymmetric plasmonic slot waveguide configuration with enhanced LMI is employed to shrink the device footprint further. A small interaction length of 1.6 µm presents a low device capacitance which aided in realizing ultra-low switching energy of 86.45 aJ/bit and modulation bandwidth over 1 THz.

Keywords: On-chip integrated modulator, Graphene, Indium Tin Oxide, Broadband, Electroabsorption modulator, Energy efficient.