Ultrafast Epsilon-Near-Zero Electroabsorption Modulators

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Conventional silicon photonic modulators based on thermo-optic or plasma dispersion effects face an inherent tradeoff between optical bandwidth and size due to a weak light-matter interaction. Mach-Zehnder modulators based on carrier depletion provide fast and broadband modulation, but usually require high voltages and/or long active region lengths due to the weak plasma dispersion effect in silicon. Alternatively, highly-resonant modulators reduce power dissipation and increase integration density, but usually exhibit precise active temperature control and narrowband wavelength acceptance.

Another approach to realizing broadband, compact, energy-efficient modulators entails the increase of light-matter interaction by tightly confining light using plasmonic or epsilon-near-zero (ENZ) effects. Here, we focus on ENZ confinement, which occurs near a material's dielectric-metallic transition wavelength where the real part of the permittivity crosses zero; close to this ENZ wavelength, light can be confined into deeply sub-wavelength geometries and reach correspondingly high field intensities. Transparent conducting oxides (TCOs) such as indium oxide (In_2O_3) and cadmium oxide (CdO) are a useful class of materials for exploiting ENZ confinement due to having ENZ points in the near- to mid-infrared (depending on carrier concentration) as well as having the ability to tune the real ENZ crossing by accumulating or depleting carriers in the oxide film either optically or electrically.

We experimentally demonstrate high-speed digital modulation in integrated optical modulators based on ENZ effects that operate at data rates up to 2.5 Gb/s with a 2 Vpp (peak-to-peak) drive voltage. We observe larger than 6.5 dB extinction ratio in a 4 µm long modulator across a wavelength range of 1530 nm – 1590 nm. We further investigate theoretically the impact of mobility in TCOs, whose increase leads to a decrease of the imaginary part of the permittivity at the ENZ wavelength. We will show that modulators containing CdO show improved performance through a reduction in loss in the off-state and increased absorption in the on-state, enabling sub-micron lengths with greater than 5 dB extinction ratios. We envision a new class of high-speed modulators for integrated photonics enabled by these results.

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