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Multiphysics Modeling of Electro-Optic Devices

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Outline

• Combined RF-Optical mode analysis
  – RF waveguide mode
  – Optical waveguide modes
  – Electro-optic interaction

• Combined wave propagation
  – Paraxial optical propagation
  – DC modulation
  – Time-dependent RF modulation
The Workhorse Electro-Optic Device: Mach-Zehnder Interferometer

\[ P_{out} = \frac{P_{in}}{2} \left[ 1 + \cos \left( \frac{\pi (V_{DC} + V_{RF})}{V_{\pi}} \right) \right] \]

\[ \Delta \phi = 0 \quad \Delta \phi = \pi \]
Coplanar Waveguide Structure

Electrodes
Buffer Layer
Substrate

Optical waveguides
Geometry for RF and Optical Mode Solving in Comsol

w = 8 µm, g=28 µm, t_m = 30 µm, t_b = 1 µm, ε_b = 3.8, ε_sub = [28, 44, 44]

Optical waveguide profile is defined by diffusion equation
Electric Displacement Field ($D_x$) of RF Mode
RF Mode Effective Index and Loss vs. Frequency

\[ \alpha = -2\pi f \text{ Im}(n_{\text{eff}})/c \]
Characteristic Impedance vs. Frequency

\[ Z_0 = \frac{2 \pi}{|I|^2} \]
Optical Waveguide Mode Splitting with Applied E-Field

\[ \Delta n_{o/e} = -\frac{1}{2} n_{o/e} r_i^3 E_x \]
Velocity Matching Bandwidth and Half-Wave Voltage vs. Device Length

\[ f_c = \frac{c}{2 n_m L \delta} \]
\[ \delta = 1 - \left( \frac{n_o}{n_m} \right) \]
\[ V_{\pi} = \frac{\lambda}{2 (\Delta n/V) L} \]
[does not incorporate electrode losses]
Simplified 2D MZI Model with DC Electrodes

- Scalar Paraxial Wave Equation for Optics
- Electrostatics
- Stationary Solution
Transmission of 2D MZI Model vs. DC Voltage
Simplified 2D MZI Model with RF Electrodes

- Time-Dependent EM Wave Propagation for RF
- Scalar Paraxial Wave for Optics (stationary solution at each time step)

Input/Output Waveforms @f_{in} = 1 GHz
Conclusions

• Comsol Multiphysics provides complete capabilities for modeling of electro-optic devices

• With adequate computational resources, 3D EO propagation models are possible