Modeling of plasmonic organic hybrid E/O modulators: towards a comprehensive 3D simulation framework

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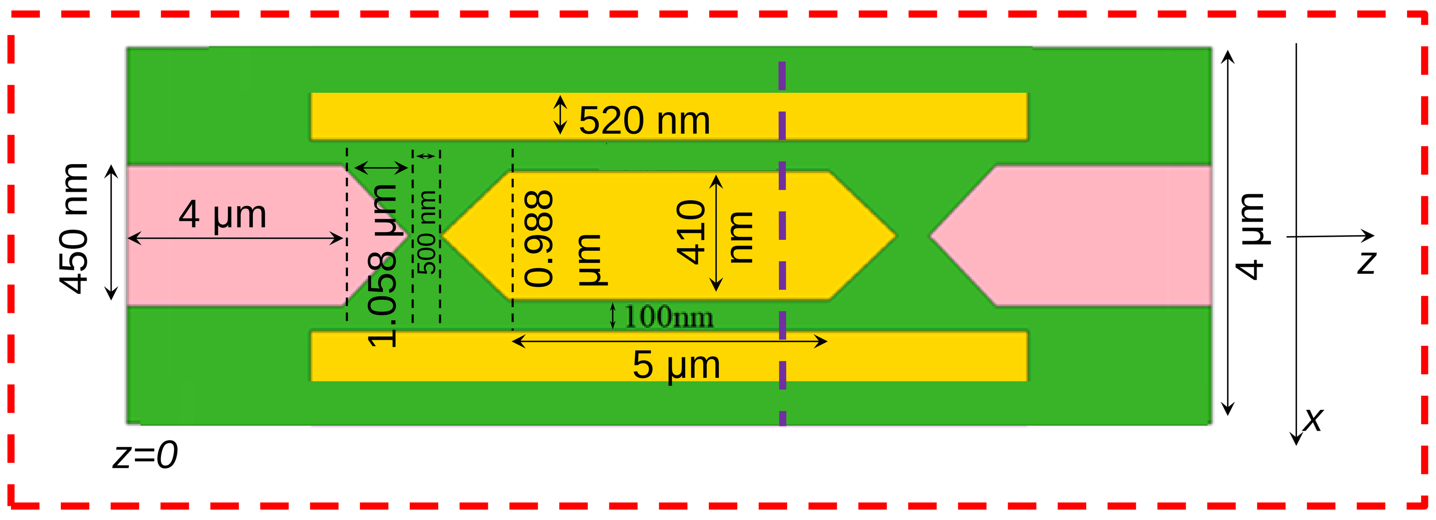
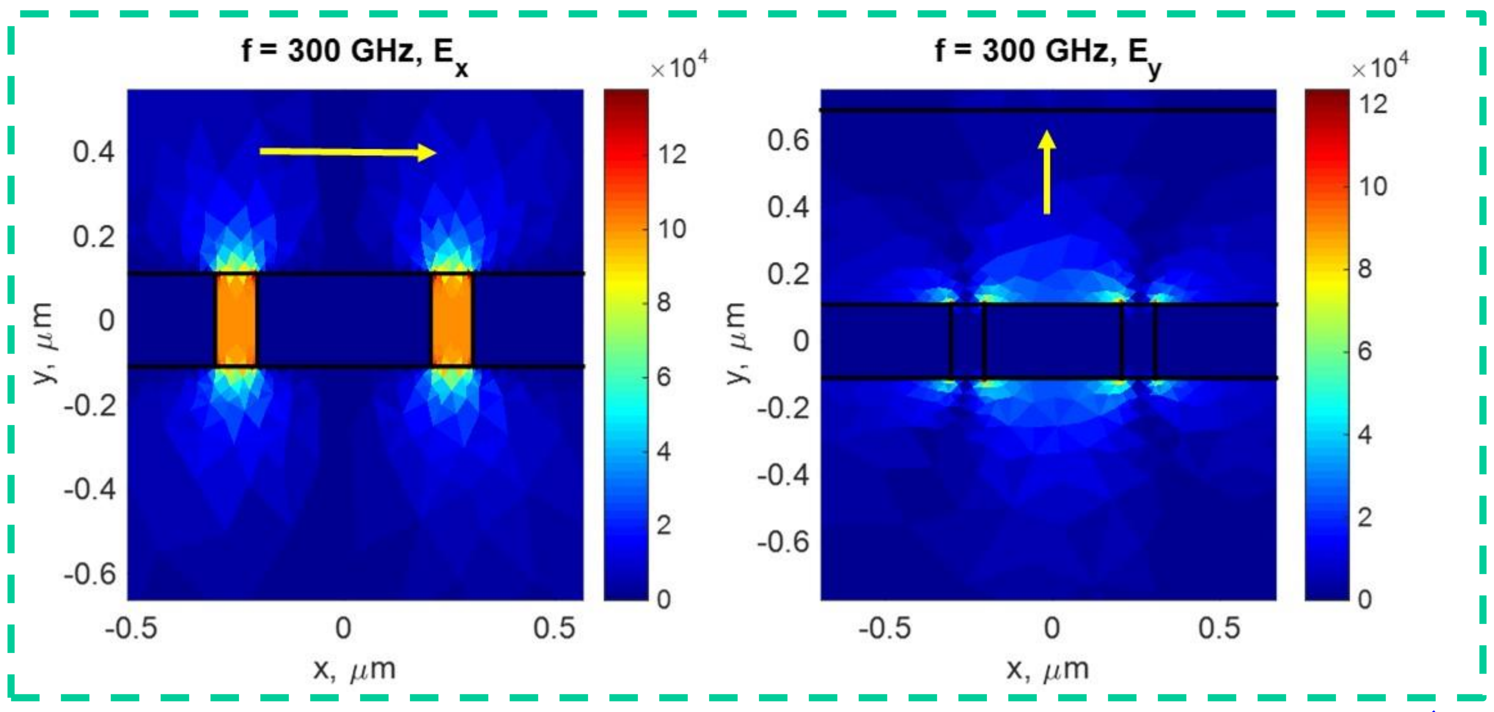
The work focuses on the simulation of plasmonic organic hybrid electro/optic modulators. Preliminary multiphysics-augmented simulations of the slot waveguide are presented. Instead of applying them in system-level models, they are combined with the results of 3D finite-difference time-domain (FDTD) simulations to achieve realistic physics simulations at moderate computational costs. The model is demonstrated on a device from the literature and validated through a comparison with 3D-FDTD simulations of the entire device.

Multiphysics-augmented slot waveguide simulation



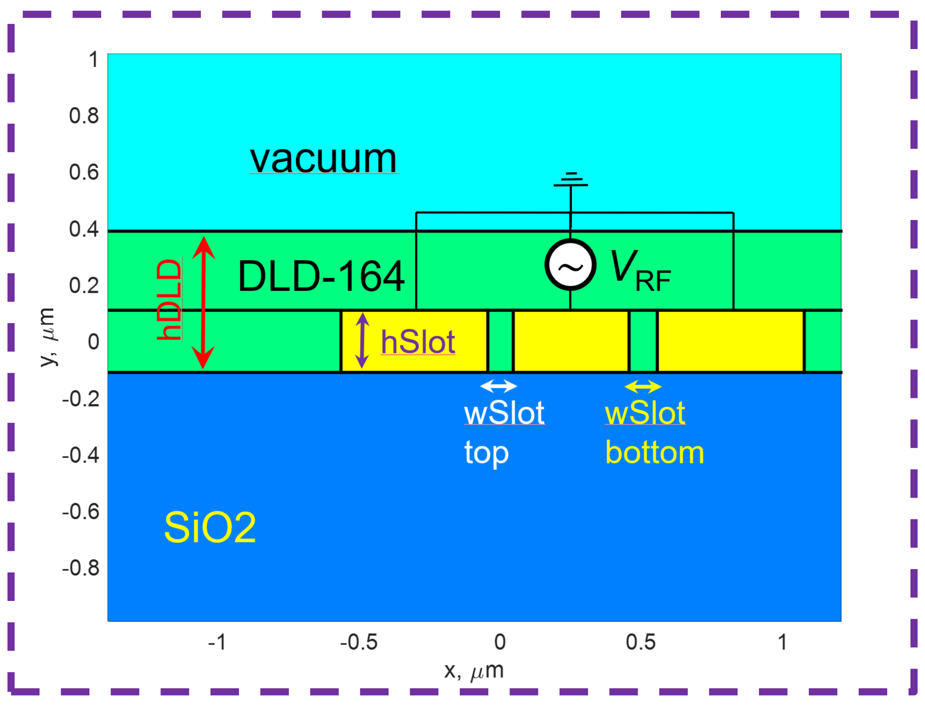
Top view of the device under investigation from Haffner et al., Nature Photon., vol. 9, pp. 525–528, July 2015

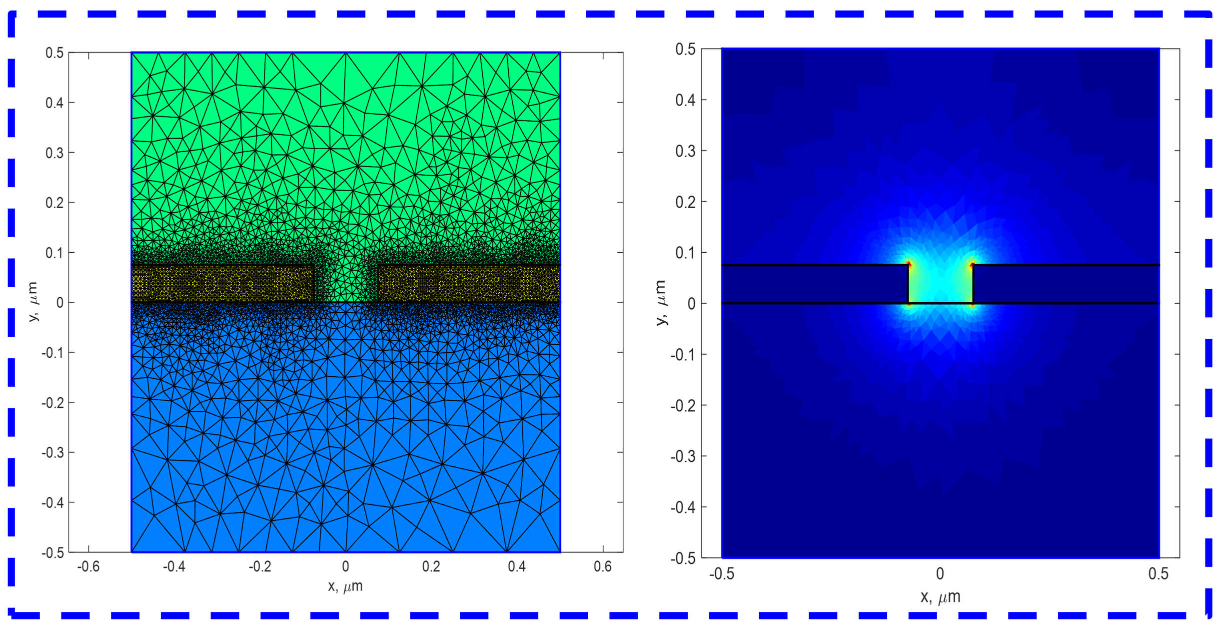


The RF field exhibits both x-directed and y-directed components, both contributing to the electro/optic effect. From this field profile, a map of refractive index change, $\Delta n_{\text{mat}}(x,y)$, is obtained as

$$\Delta n_{\text{mat}} = \frac{1}{2} r_{33} n_{\text{NLO}}^3 \sqrt{E_x^2 + E_y^2}$$

The cross-section indicated in the top view as a vertical purple line is shown here. DLD-164 is the E/O polymer, reacting to the RF field applied to the two slot waveguides realizing the phase modulator.





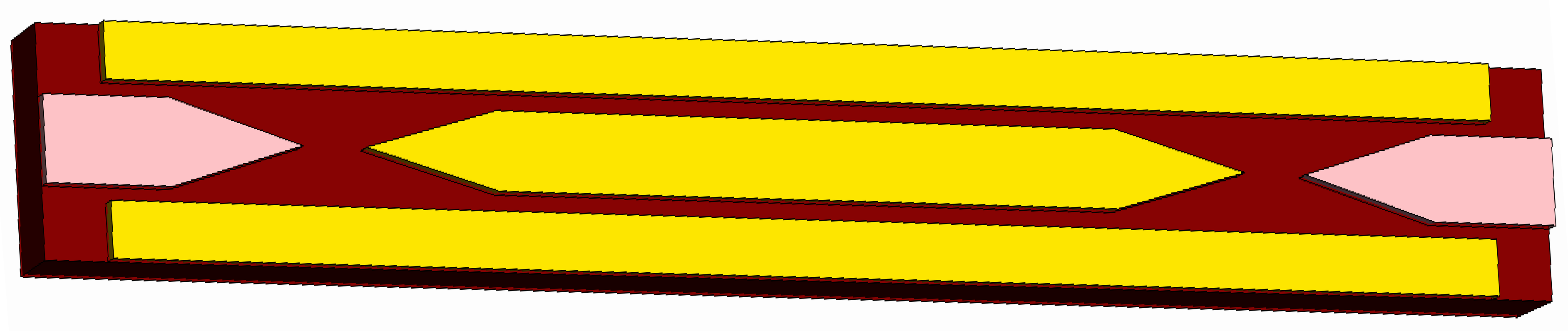
The refractive index change is used as input of the optical waveguide simulator, which estimates the mode features of the waveguides. E/O effect is enhanced by the strongly-localized plasmonic mode (left, optical mesh; right, fundamental plasmonic mode)

Divide-et-impera simulation strategy

Waveguide simulations are usually adopted in system-level models. Even providing a rough idea of the modulator response, such models are not sufficient to achieve realistic estimates of the main figures of merit, *e.g.*, extinction ratio (ER), insertion loss (IL).

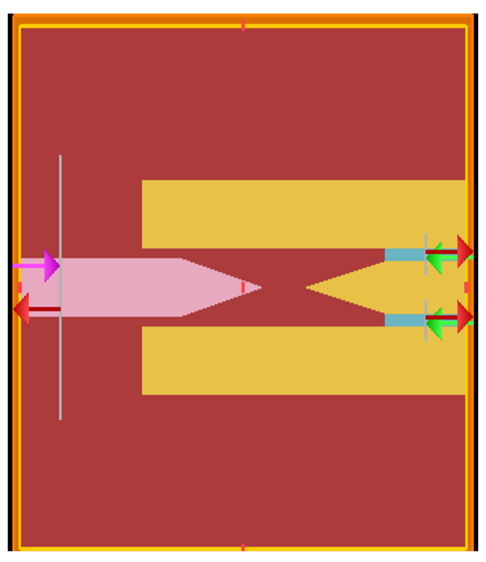
Better realism can be achieved from 3D-FDTD simulations of the entire device, which are very computationally-intensive.

An intermediate approach between *all-in-one* 3D-FDTD simulations and system-level models can be achieved by identifying the POH E/O Mach-Zehnder modulator with a bimodal Fabry-Pérot interferometer.

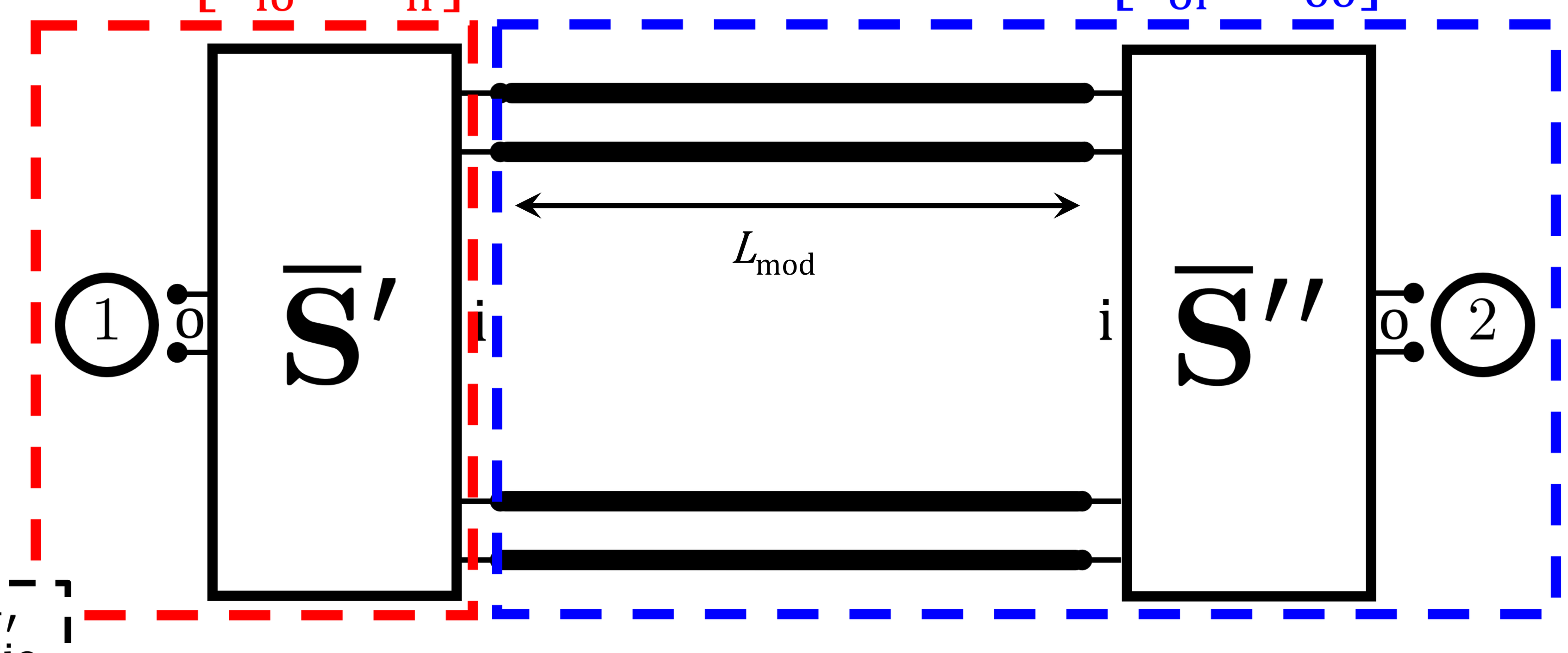


In this approach, the only component requiring 3D-FDTD simulation (only at 0 V!) is the splitter.

The FDTD solver returns scattering matrices of the splitter, including a piece of transmission line, to be de-embedded analytically.



$$\bar{\mathbf{S}}' = \begin{bmatrix} \bar{\mathbf{S}}'_{\text{oo}} & \bar{\mathbf{S}}'_{\text{oi}} \\ \bar{\mathbf{S}}'_{\text{io}} & \bar{\mathbf{S}}'_{\text{ii}} \end{bmatrix} \qquad \bar{\mathbf{S}}'' = \begin{bmatrix} \bar{\mathbf{S}}''_{\text{ii}} & \bar{\mathbf{S}}''_{\text{io}} \\ \bar{\mathbf{S}}''_{\text{oi}} & \bar{\mathbf{S}}''_{\text{oo}} \end{bmatrix}$$



$$\mathbf{E}_{\text{port}} = \begin{bmatrix} \exp\left(jk_0 n_{\text{eff,i,1}} L_{\text{port}}\right) & 0 \\ 0 & \exp\left(jk_0 n_{\text{eff,i,2}} L_{\text{port}}\right) \end{bmatrix}$$

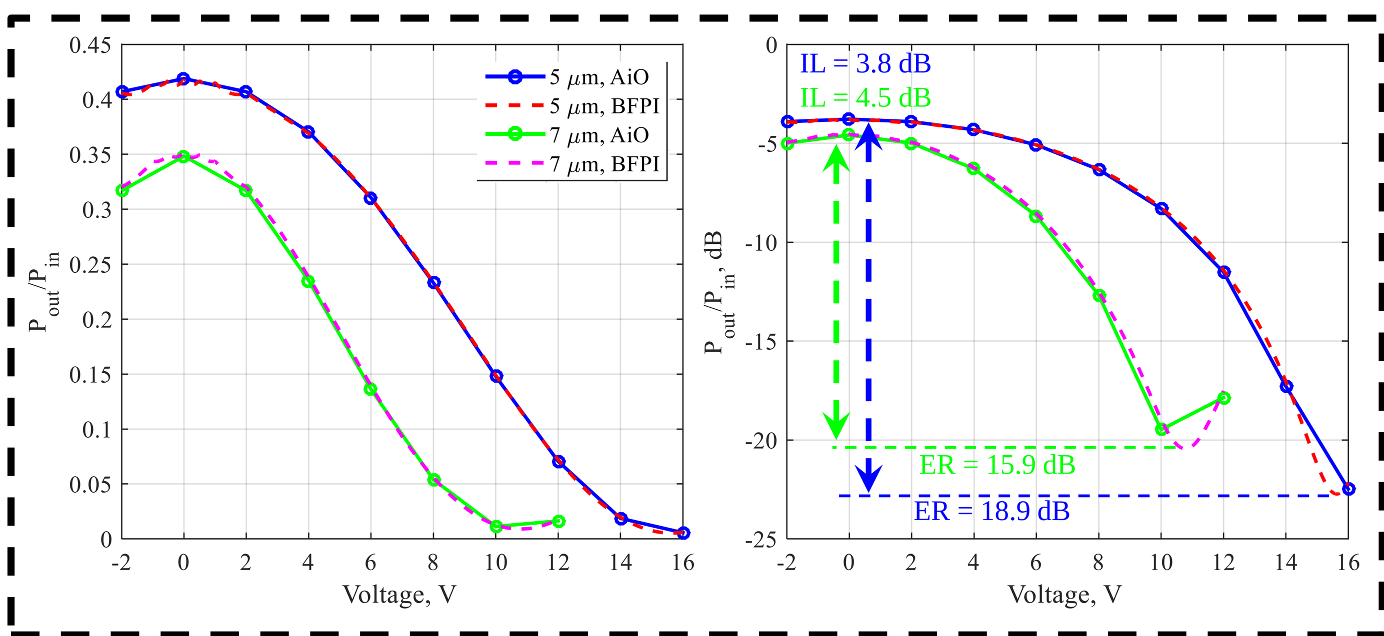
$$\bar{\mathbf{S}}'_{\text{ii}} = \mathbf{E}_{\text{port}}^{-1} \bar{\mathbf{S}}^{\text{L}}_{\text{ii}} \mathbf{E}_{\text{port}}^{-1}$$
$$\bar{\mathbf{S}}'_{\text{io}} = \mathbf{E}_{\text{port}}^{-1} \bar{\mathbf{S}}^{\text{L}}_{\text{io}}$$
$$\bar{\mathbf{S}}'_{\text{oi}} = \bar{\mathbf{S}}^{\text{L}}_{\text{oi}} \mathbf{E}_{\text{port}}^{-1}$$
$$\bar{\mathbf{S}}'_{\text{oo}} = \bar{\mathbf{S}}^{\text{L}}_{\text{oo}}$$

$$S_{11} = \bar{\mathbf{S}}'_{\text{oo}} + \bar{\mathbf{S}}'_{\text{oi}} \bar{\mathbf{S}}''_{\text{ii}} [\mathbf{I} - \bar{\mathbf{S}}'_{\text{ii}} \bar{\mathbf{S}}''_{\text{ii}}]^{-1} \bar{\mathbf{S}}'_{\text{io}}$$
$$S_{12} = \bar{\mathbf{S}}'_{\text{oi}} [\mathbf{I} - \bar{\mathbf{S}}''_{\text{ii}} \bar{\mathbf{S}}'_{\text{ii}}]^{-1} \bar{\mathbf{S}}''_{\text{io}}$$
$$S_{21} = \bar{\mathbf{S}}''_{\text{oi}} [\mathbf{I} - \bar{\mathbf{S}}'_{\text{ii}} \bar{\mathbf{S}}''_{\text{ii}}]^{-1} \bar{\mathbf{S}}'_{\text{io}}$$
$$S_{22} = \bar{\mathbf{S}}''_{\text{oo}} + \bar{\mathbf{S}}''_{\text{oi}} [\mathbf{I} - \bar{\mathbf{S}}'_{\text{ii}} \bar{\mathbf{S}}''_{\text{ii}}]^{-1} \bar{\mathbf{S}}'_{\text{ii}} \bar{\mathbf{S}}''_{\text{io}}$$

$$\mathbf{E}_{\text{mod}} = \begin{bmatrix} \exp\left(jk_0 n_{\text{eff,i,1}}(V) L_{\text{mod}}\right) & 0 \\ 0 & \exp\left(jk_0 n_{\text{eff,i,2}}(V) L_{\text{mod}}\right) \end{bmatrix}$$

$$\bar{\mathbf{S}}''_{\text{ii}} = \mathbf{E}_{\text{mod}} \bar{\mathbf{S}}'_{\text{ii}} \mathbf{E}_{\text{mod}}$$
$$\bar{\mathbf{S}}''_{\text{io}} = \mathbf{E}_{\text{mod}} \bar{\mathbf{S}}'_{\text{io}}$$
$$\bar{\mathbf{S}}''_{\text{oi}} = \bar{\mathbf{S}}'_{\text{oi}} \mathbf{E}_{\text{mod}}$$
$$\bar{\mathbf{S}}''_{\text{oo}} = \bar{\mathbf{S}}'_{\text{oo}}$$

The multiphysics waveguide simulations presented in the top part can be used to define the matrix **S''** as equal to **S'**, but with reference planes changed accordingly to the voltage-dependent phase-shift:



The results obtained with all-in-one 3D-FDTD simulations (AiO) are compared to those achieved with the bimodal Fabry-Pérot interferometer model (BFPI) for two devices having 5 µm (blue/red curves) and 7 µm modulator length (green/magenta curves).