Electronic Supplementary Information (ESI) for Electro-Optic Metasurface-Based Free-Space Modulators

Christopher Damgaard-Carstensen*, Martin Thomaschewski, and Sergey I. Bozhevolnyi*

Centre for Nano Optics, University of Southern Denmark,

Campusvej 55, DK-5230 Odense M, Denmark

*To whom correspondence should be addressed:

cdc@mci.sdu.dk, seib@mci.sdu.dk

Number of pages: 5

Number of figures: 4

1 Optimization for TE polarization

An optimization is performed for TE polarization in the same manner as for TM polarization (Figure S1). The available design parameters of stripe width, stripe thickness, and unit cell period are varied iteratively to obtain a deep and narrow resonance. The strongest resonance is achieved at a wavelength of 914 nm for the following parameters: $t_{LN} = 320\,\text{nm}$, $t_g = 50\,\text{nm}$, $\Lambda = 600\,\text{nm}$, and $w = 290\,\text{nm}$. When applying a modulation voltage of ± 10 V, a maximum modulation depth similar to that obtained for TM polarization is achieved (~ 100 %), but the difference in reflection coefficient amplitude is reduced by a factor of two, resulting in lower reflectivity of the modulator. This design functions at a shorter wavelength and performs slightly worse than that described in the main text, but still displays very high expected modulation depth.

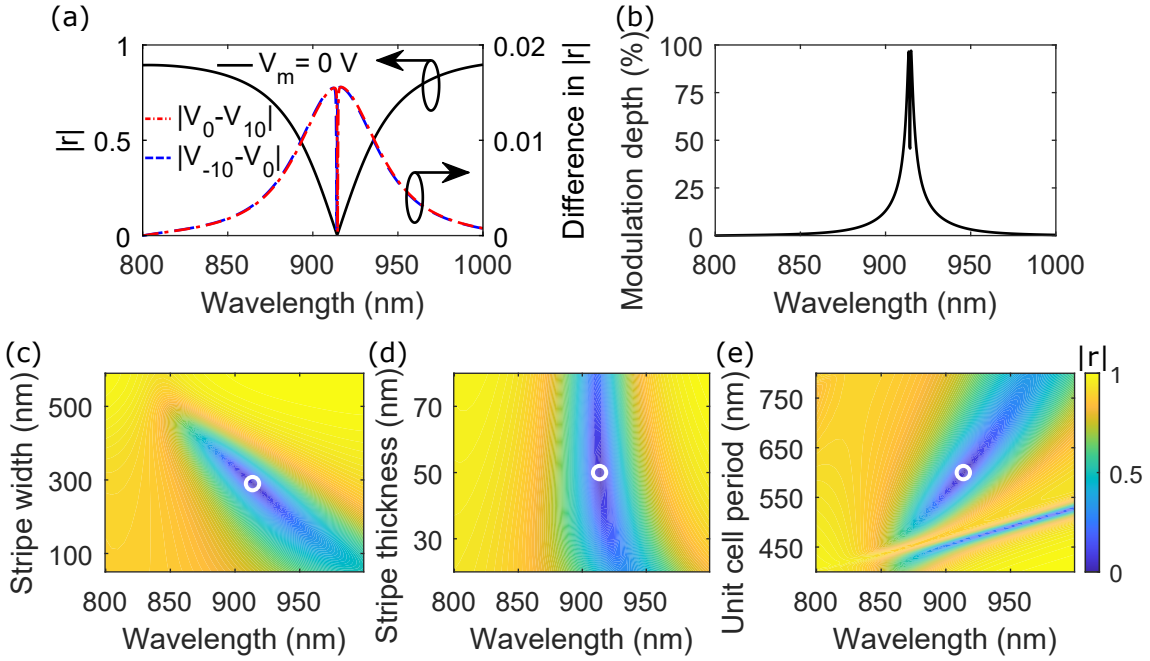

Figure S1: Optimization for TE polarization. (a) Calculated reflection coefficient amplitude as a function of wavelength without applying a modulation voltage (left axis), and difference in reflection coefficient amplitude when applying a DC modulation voltage of ± 10 V (right axis). (b) Calculated modulation depth from the graphs of (a). (c-e) Color maps of calculated reflection coefficient amplitude as a function of wavelength and (c) stripe width, (d) stripe thickness, and (e) unit cell period, with white circles representing the selected parameter values for the modulator design. Parameters not under investigation are: $t_{LN} = 320\,\text{nm}$, $t_g = 50\,\text{nm}$, $\Lambda = 600\,\text{nm}$, and $w = 290\,\text{nm}$

2 Field distributions for optimized designs

Field profiles are shown at resonance in the xz-plane for designs optimized for TM and TE polarization, respectively (Figure S2). All field plots show a strong confined field in the lithium niobate thin film for a maximized spectral resonance shift. At the Fabry-Perot resonance, we expect light reflected from the nanostripe and light reflected from the gold back-reflector to be out of phase. The field profiles show a shift of $1.5\lambda_0$ between light reflected from the nanostripe and gold back-reflector resulting in the expected phase shift, which substantiates that we are working around a Fabry-Perot resonance.

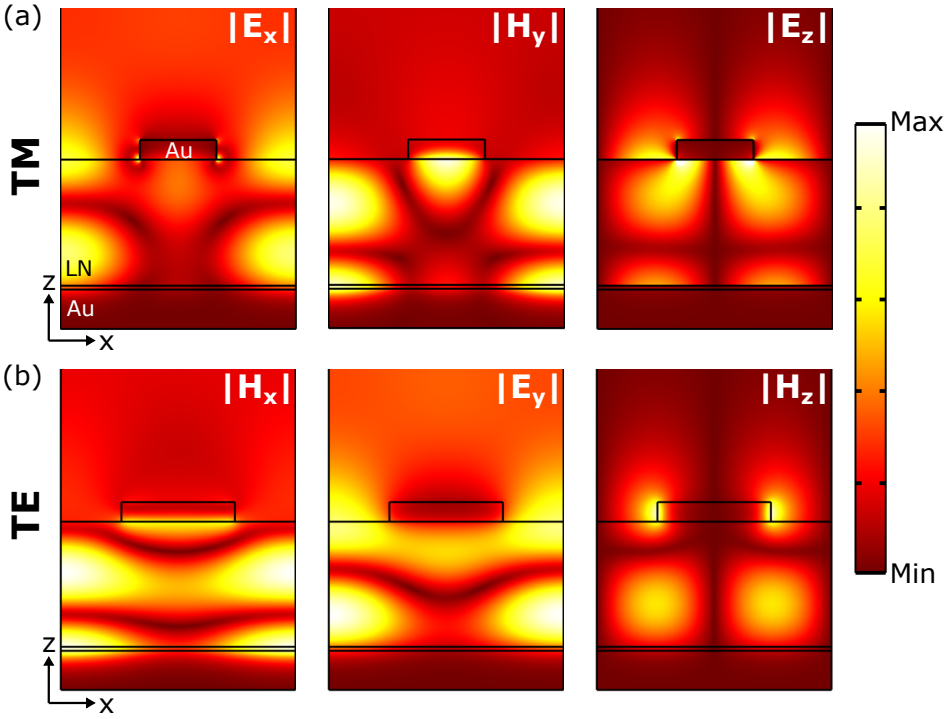

Figure S2: Field profiles at resonance in the xz-plane. (a) Absolute value of the E_x (left panel), H_y (middle panel), and E_z (right panel) field components for a TM polarized normally incident wave. (b) Absolute value of the H_x (left panel), E_y (middle panel), and H_z (right panel) field components for a TE polarized normally incident wave.

3 Optimization for polarization independence

By using a nanostripe design instead of a continuous top gold film we lose the inherent polarization independence. However, it is still possible to optimize the design for polarization independent modulation (Figure S3). We do this by starting from the design optimized for TM polarization. Of the available design parameters, the stripe width and unit cell period show the biggest influence on the performance, so these parameters are varied to achieve the strongest modulation depth for both polarizations. This is achieved at the following parameters: $t_{LN} = 320\,\text{nm}$, $t_g = 50\,\text{nm}$, $\lambda_0 = 930\,\text{nm}$, $\Lambda = 540\,\text{nm}$, and $w = 185\,\text{nm}$. The best polarization independent modulation of $\sim 30\,\%$ is obtained at the point indicated by the red dashed lines. This is a factor of three lower than for designs optimized for a single polarization.

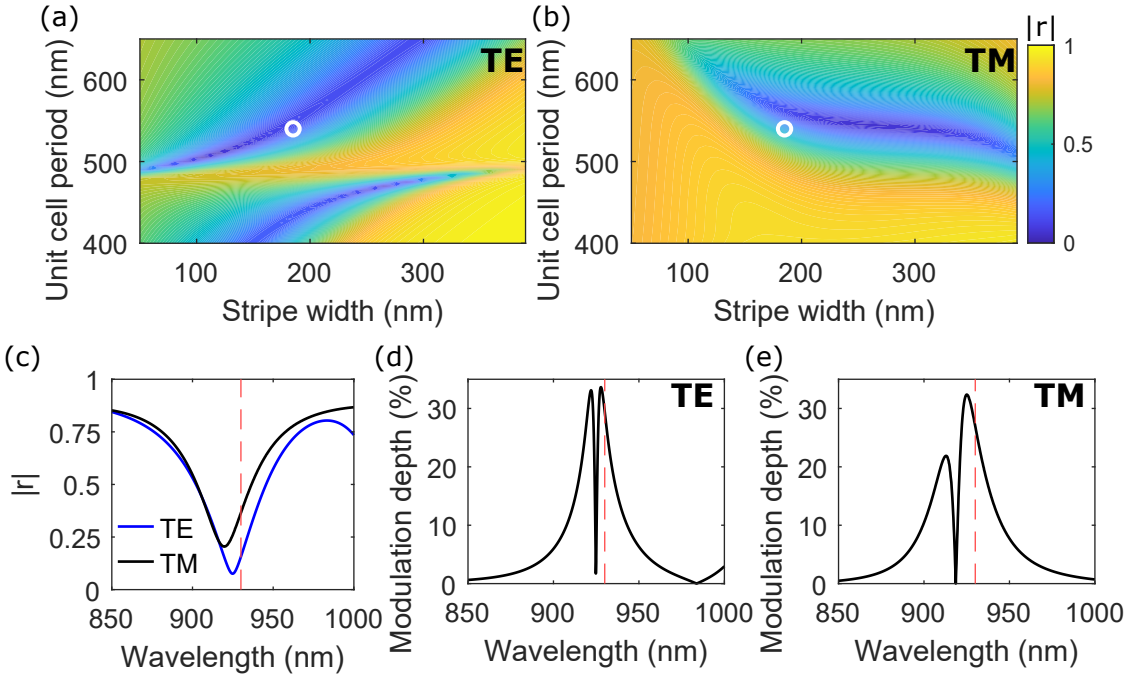

Figure S3: Simulations for polarization independent modulator. (a,b) Color maps of calculated reflection coefficient amplitude for (a) TE and (b) TM polarization for varying unit cell period and stripe width. White circles represent the common point of strongest resonance for both polarizations, thus giving the parameters for the polarization independent modulator: $t_{LN} = 320\,\text{nm}$, $t_g = 50\,\text{nm}$, $\lambda_0 = 930\,\text{nm}$, $\Lambda = 540\,\text{nm}$, and $w = 185\,\text{nm}$. (c) Plots of calculated reflection coefficient amplitude as a function of wavelength, displaying the two similar resonance dips. (d,e) Calculated modulation depth for (d) TE and (e) TM polarizations showing a polarization independent modulation of 30 %. Red dashed lines indicate the point of strongest polarization independent modulation.

4 Modeling of titanium adhesion layer

Titanium adhesion layers are notoriously hard to model due to their very low thickness. However, they are known to affect the performance, and so we have tried to recalculate the modulation depth based on a model that includes a 3 nm titanium adhesion layer between the LN gold nanostripes (Figure S4). The calculated modulation depth experiences a reduction by 50 % when including the titanium adhesion layer in the model. Furthermore, this is considered an ideal 3 nm layer. In reality, evaporating such thin films will cause very high non-uniformity, thus leading to inhomogeneous absorption and scattering, which will further affect the performance.

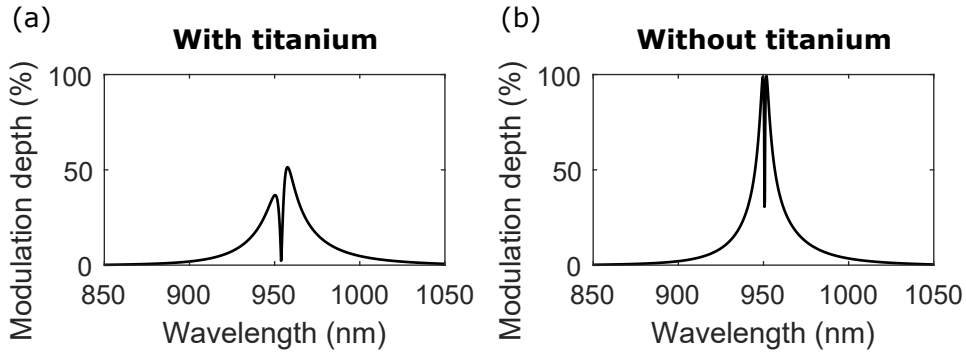

Figure S4: Simulations for influence of titanium adhesion layer. (a) Plot of the calculated modulation depth based on a model that includes the 3 nm titanium adhesion layer between LN and gold nanostripes. (b) Plot of calculated modulation depth without considering the titanium adhesion layer. Identical to Figure 1d in the main text.