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Digital Plasmonic Absorption Modulator Exploiting Epsilon-Near-Zero in Transparent Conducting Oxides

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Digital Plasmonic Absorption Modulator
Exploiting Epsilon-Near-Zero in
Transparent Conducting Oxides

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Abstract: Optical switches operated around $\epsilon$-near-zero (ENZ) of transparent conducting oxides (TCOs) are analyzed. A digital optical switching behavior is derived – quite different from earlier predictions. The digital modulation characteristic originates from the fact that the nonlinear switching is to a large extent performed in the ENZ layer. The ENZ layer, however, is arising from carrier accumulation in the TCO and confined to a relatively thin layer with a characteristic dimension that does not change upon applying a higher voltage. An accurate treatment of this inhomogeneous layer is vital to reliably predict the modulation characteristics. Such nonlinear accumulation processes and inhomogeneous material properties require refined simulations for which reason we apply an iterative solver based on a high order finite element method. More precisely, we solve the nonlinear stationary quantum hydrodynamic model to derive the carrier concentration upon applying an electrical field across the modulator. The result is then directly coupled to Maxwell’s equation, which shows a strong local enhancement of the electromagnetic fields in the ENZ layer. In an exemplary implementation, we forecast the feasibility of 6 $\mu$m long TCO absorption modulators with on-state losses of 2.8 dB and extinction ratios above 10 dB.

Index Terms: Plasmonics, Non-linear effects in nanostructures, Optoelectronic materials, Waveguide devices, Modeling, Ultrafast nonlinear processes, Modulators, Transparent conducting oxides, $\epsilon$-near-zero materials

1. Introduction

Electro-optical modulators are key components for the on-chip integration of optical circuits. They should feature large bandwidth, high speed, low footprint [1-3] and at best offer a digital transfer function – all of which at the same time. Absorption modulators based on carrier accumulation or depletion in transparent conducting oxides (TCOs) are a promising class thereof as introduced in [4]. TCOs are well suitable materials for modulation in the near infrared (NIR) because their plasma frequency is close to telecommunication wavelengths. Hence, local changes in the carrier density will have a strong impact on the optical properties of the TCO [5, 6]. Since electron accumulation is an ultrafast process, such devices are only limited by the RC time constant and offer modulation speeds in the THz regime [7-9]. Therefore, TCO-based plasmonic electro-optical modulators should be ultrafast, ultracompact and energy-efficient [10].

Plasmonic electro-optical modulators are a very active research topic whose latest progress is nicely summarized in some reviews [11-14]. Recently, new plasmonic organic hybrid waveguides were introduced demonstrating operation beyond 108 Gbit/s [15-17]. In these plasmonic organic hybrid waveguides, light is modulated by means of an organic material with a large linear electro-optic effect. Since the linear electro-optic effect changes the phase of the light, these waveguides were realized in a Mach-Zehnder (MZ) configuration to modulate the amplitude through constructive or destructive interference at the output [16, 17]. Although MZ modulators are versatile, because
they enable modulation of both the amplitude and phase, simpler schemes might be advantageous when only on-off keying is needed. So in this context, direct absorption modulators such as TCO-based electro-optical modulators [14, 18] become interesting, as they do not need splitting and combining of waveguides and therefore are simpler. Two working principles for absorption modulation with TCOs have been proposed so far, latching switches and carrier accumulation modulators. The first are based on the formation of a conductive path between the electrodes [19]. They are limited in speed to the MHz regime but show a hysteresis effect, which makes them also good candidates for optical memories. The ones based on carrier accumulation should be ultra-fast and have been studied theoretically for a large variety of waveguide designs [4, 7-9, 20-30]. To theoretically predict the performance of the latter, the carrier accumulation was either assumed or computed with the Poisson equation like in Thomas-Fermi theory and subsequent averaging to an accumulation layer. All papers predict remarkable TCO-based modulation. However, the experimental verification is very challenging and hence still an open issue. Current work [4, 7, 9, 25, 26, 31] could not yet show the high speed operation which is inherent to electron accumulation processes although some first indications at 500 MHz were recently published [31]. This is in part because fabrication is challenging and some experiments were limited by RC time constants due to large dimensions [4, 26]. To some other part, high speed was probably not possible because the latching switch scheme [19] was observed rather than the ultrafast plasma dispersion effect. Lastly, the ultrafast switching performance might not yet have been found because the true operation principle might be more intricate and proper operation requires a better design. Hence, a profound understanding based on an accurate theoretical modeling is essential in order to find experimental proof.

In this paper, we theoretically investigate TCO-based plasmonic absorption modulators exploiting ENZ absorption enhancement through carrier accumulation. The results are quite different from previous work [4, 7-9, 20-30] and predict a digital optical switch behavior. For our calculations, we derive the inhomogeneous optical properties from a quantum hydrodynamic (QHD) model and directly incorporate them into an electromagnetic mode solver. This allows a more accurate modeling of the effect as no intermediate averaging is required. In particular, we compute the electron accumulation process as a stationary solution of the QHD equation including quantum pressure [32]. Then, the exponentially increasing carrier distribution is directly incorporated to Maxwell’s equation with an inhomogeneous Drude permittivity. Applying this model to a representative TCO plasmonic absorption modulator, we find a strong local field enhancement due to operation at e-near-zero (ENZ) [20, 33] as main mechanism for absorption modulation. Since the ENZ region is spatially limited, we observe digital absorption modulation. Our example of a hybrid plasmonic waveguide has an extinction ratio of 1.7 dB/µm for a voltage of 1.5 V and low on-state propagation loss of 0.5 dB/µm.

2. Concept

Plasma dispersion in conducting materials is a known effect for the modulation of the permittivity by accumulation or depletion of free carriers. If performed in plasmonic structures, it enables light modulation at highest speed with an ultracompact footprint [3, 34-36]. The compact size is due to the fact that electromagnetic fields are strongly confined in plasmonic structures while the high speed is achievable thanks to an ultrafast accumulation process and strongly reduced RC time constants in such compact devices. In comparison to photonic absorption modulators, the bandwidth increases from a few nanometers to >100 nm and the footprint reduces from 100 – 1000 µm² to less than 10 µm², while both energy consumption and speed are comparable [2, 13, 14].

A plasmonic absorption modulator is depicted in Fig. 1(a) to illustrate the switching behavior. Light propagating along a standard silicon-on-insulator (SOI) waveguide is guided into a hybrid plasmonic waveguide [37] that serves as a modulator. In the modulator section, the silicon waveguide is covered by a thin layer of TCO, a dielectric thin film and a metal on top [7, 19]. The metal serves as the guiding layer for the surface plasmon polariton (SPP) mode. Behind the modulator section, the signal is coupled back to a SOI waveguide and fed into an optical network.
In the hybrid section, we choose a TCO as the active material because it shows a strong plasma dispersion effect in the NIR [14]. Furthermore, since a TCO is a good conductor, it also serves as the ground electrode of the device. The thin dielectric layer is an insulator and acts as charge blocking layer. It should have a high static permittivity for low power operation and a large band gap to prevent electrical breakdown [38]. The top metal layer serves as a second electrode and as a plasmonic layer that guides and confines the SPPs along the active modulator layer.

![Image](image.png)

**Fig. 1:** (a) The structure of a plasmonic absorption modulator and (b) its digital transfer function when applying a voltage between the metal and the TCO. The bottom insets illustrate how electrons (small spheres) are accumulating at the TCO-insulator interface when the modulator is forward biased. When increasing the voltage from 0 V to 1.5 V, carriers accumulate at the interface and cause a strong increase of the optical absorption. The large absorption on the one hand is a result of an increase in the free carriers in the accumulation layer. On the other hand, it mainly stems from a strong change in the optical properties of the TCO that leads to a new distribution of the optical field in the waveguide (the solid white line depicts $|E_z|$). When further increasing the voltage from 1.5 V to 3 V the peak in the optical field is not further increased but rather shifted. The absorption characteristic flattens – thus leading to a digital transfer function.

The operation principle of a TCO-based modulator is exploiting the plasma dispersion effect and the ENZ absorption enhancement due to free carrier accumulation [4, 7-9, 20-30]. Without a bias, the electromagnetic mode ($|E_z|$) in the active section has the well-known hybrid shape, see left bottom inset of Fig. 1. The switch then has low propagation losses. Hence, the modulator is in its transmitting on-state. When a forward bias is applied to the metal electrode, free carriers in the TCO accumulate at the interface to the insulator (cf. middle and right bottom inset of Fig. 1). This carrier accumulation locally changes the optical properties of the TCO material from dielectric to metallic. The crossing region where the permittivity changes its sign (i.e. the ENZ region) gives rise to a large field enhancement in the TCO layer. Importantly, the TCO is a lossy material and thus this leads to a strong absorption enhancement, i.e. the modulator is in its absorbing off-state.

The absorption modulation has a digital transfer function. This is because the ENZ area that absorbs is well-defined and will not change its size when the applied voltage is increased beyond a saturation point. Once the full ENZ extent is exploited, applying higher voltages will start to induce metallic properties at the interface. Therefore, it will move the transition from dielectric to metallic behavior from the interface into the TCO layer. Thereby, the ENZ area and the accompanying field peak are shifted but not increased further (cf. middle and right bottom inset of Fig. 1). This limitation of ENZ results in a flattening of the extinction ratio and leads to a two level absorption system as shown in Fig. 1(b). Hence, a TCO-based absorption modulator is in fact a digital switch.

The advantages of the hybrid plasmonic modulator concept are low loss, high speed, and an ultracompact size. The hybrid structure of the waveguide is beneficial as it enables high coupling efficiencies from the silicon photonic waveguide to the plasmonic mode and vice versa. The hybrid waveguide also represents a good compromise between a high plasmonic field confinement to the active region and the propagation loss [7, 19]. The ultracompact size is due to the high field
enhancement in plasmonics that reduces the required interaction length from several millimeters in photonics to a few micrometers in plasmonics. The high speed is due to a drastically reduced RC time constant. The resistance is small because the electrodes comprise of conducting materials like metals or TCOs. The overall capacitance is small, as the electro-optic section is small. Since the drifting time of electrons in TCOs is extremely short, ultrafast modulation speeds in the THz regime should be available [4, 7]. However, currently proposed TCO modulators are limited by the RC time constant and hence operate with a few tens of GHz. For our design of a 6 μm long modulator, we get a resistance of about 50 Ω by estimating the contribution of the TCO electrode through its resistivity [39] and by neglecting the minor influence of the gold contacts. Furthermore, we assume a plate capacitor with a geometry as shown in Fig. 2 to estimate a capacitance of 100 fF. This results in an electrical modulation speed of about 30 GHz and an energy consumption of 60 fJ/bit at a voltage of 1.5 V. Since the response of light to the plasma dispersion effect is much faster than the RC limit, we can safely neglect any delay from the decay of strong local fields. Hence, the electrical modulation speed of about 30 GHz directly translates to the optical domain.

3. Calculation of Carrier Accumulation in TCO Layers

Switching in the absorption modulator is based on the carrier accumulation effect. Therefore, an accurate description of the carrier distribution is essential before the optical mode shapes can be calculated.

The carrier distribution is often approximated by an averaged accumulation layer which is retrieved from plate capacitor theory. The description can be improved by taking the nonlocal character of the accumulation process into account. The quantum hydrodynamic (QHD) model [32, 40] provides an accurate description that considers both the dynamics and the effects of the quantum pressure. But the QHD model has more to offer. Firstly, it can be easily extended to include additional forces, e.g. from quantum potentials [41], since it describes an equation of motion. Secondly, it is also accurate for high carrier densities such as in TCOs because it does not assume a carrier distribution that e.g. follows an exponential model such as with standard classical semiconductor models [42]. Lastly, it includes electromagnetic forces which allows coupling of the QHD model to Maxwell’s equations. We therefore continue with the QHD model. To find the electrostatic potential distribution $\phi$, the Euler equation for the free carriers needs to be solved, i.e.

$$m\left(\frac{\partial \ddot{v}}{\partial t} + (\ddot{v} \cdot \nabla) \ddot{v}\right) = e \dddot{\phi} - e (\dddot{v} \times \vec{B}) - \frac{1}{n} \dddot{\nabla} p. \quad (3.1)$$

Here, $m$ is the effective electron mass, $\ddot{v}$ the carrier velocity and $n$ their density. Furthermore, $e$ is the elementary electric charge, $\vec{B}$ the magnetic flux density and $p$ the quantum pressure. In the static case, the terms including a velocity vanish and the model becomes equivalent to the Thomas-Fermi (TF) model which is a well-established technique to compute electron densities in electronics and solid-state physics [43]. Both QHD and TF model apply a quantum pressure $p = \zeta n^{5/3}$, where $\zeta = (3\pi)^{2/3} \hbar^2/(5m)$. Hence, in the static case, we have to solve the following nonlinear problem,

$$e \dddot{\phi} = \zeta \dddot{v} n^{5/3}, \quad (3.2)$$

which can be rewritten as

$$\dddot{\phi} = \frac{\zeta \dddot{v}}{e n} = \frac{5 \zeta}{3} \frac{\dddot{v}}{n^{2/3}} = \frac{5 \zeta}{2 e} \dddot{v} n^{2/3}. \quad (3.3)$$

The integration is now trivial and leads to a direct relationship between the electrostatic potential $\phi$ and the carrier density $n$,

$$\phi = \frac{5 \zeta}{2 e} n^{2/3} + C, \quad (3.4)$$

where $C$ is an integration constant which will be defined by the boundary conditions through fixing of the electric potential at the TCO electrode. Of course, the carrier accumulation must also fulfill Maxwell’s equation, i.e. Gauss’s law,

$$-\nabla \cdot (e \dddot{\phi}) = e (n_+ - n), \quad (3.5)$$
where \( n_+ \) is the ion density and \( \varepsilon \) the permittivity in the respective materials. We can assume a constant ion density due to negligible ion motion within the atomic lattice. The dielectric material is assumed to be an insulator, i.e. has no free carriers, and has a homogeneous permittivity. Therefore, (3.5) directly implies that the potential drops off linearly in the insulator. The equations (3.4) and (3.5) define a highly nonlinear problem with boundary conditions,

\[
\begin{align*}
 n &= n_+ & \text{on } \Gamma_{\text{ground}}, \\
 \phi &= 0 & \text{on } \Gamma_{\text{ground}}, \\
 \phi &= U & \text{on } \Gamma_{\text{electrode}}, \\
 \varepsilon_{\text{TCO}} \nabla \phi \big|_{\text{TCO}} &= \varepsilon_D \nabla \phi \big|_{\text{D}} & \text{on } \Gamma_{\text{interface}}, \\
 \varepsilon_{\text{TCO}} \nabla \phi \big|_{\text{TCO}} &= \varepsilon_D \nabla \phi \big|_{\text{D}} & \text{on } \Gamma_{\text{interface}}.
\end{align*}
\]

Here, \( \Gamma_{\text{ground}} \) is the boundary between Si and the TCO which is grounded, \( \Gamma_{\text{electrode}} \) the boundary between the TCO and the dielectric, \( \Gamma_{\text{interface}} \) the boundary between the dielectric and the metal electrode as shown in Fig. 2(a). \( U \) is the bias applied across the TCO layer and the insulator.

Fig. 2: (a) Schematic showing the computational boundaries for the carrier accumulation simulation and the potential distribution inside the hybrid plasmonic modulator. (b) Geometrical and material parameters of the hybrid waveguide used for illustration of the digital switching. The transverse dimension of 400 nm depicted here is a standard waveguide width which was used further above in the text to estimate the modulation speed. (c) Heights and relative permittivities [23, 44-46] used in the simulations.

Since solving (3.4) & (3.5) with boundary conditions (3.6) - (3.10) has no analytical solution, it must be solved numerically. We apply a one-dimensional finite element method (FEM) with high order elements with polynomial basis functions of degree 31. Because only the electric properties of the TCO are affected by the applied voltage, we can confine our simulation domain to the TCO. However, this prohibits to impose the applied voltage at \( \Gamma_{\text{electrode}} \) directly to our simulation boundary at \( \Gamma_{\text{interface}} \). But with the help of (3.10) and the linear potential distribution inside the dielectric, it can still be enforced indirectly. Such kind of boundary condition and especially the high nonlinearity of the problem require an iterative solver since they are impossible to be solved directly. We apply a fixed point iteration scheme using Anderson acceleration [47], i.e. we rewrite the problem such that \( \phi = g(\phi) \) and solve this by iteratively reducing the residual \( f(\phi) = g(\phi) - \phi \) through clever weighting of previous solutions. We chose a history of five previous solutions and are able to reduce the residual to double precision within only 15 iterations.

Fig. 3 shows the carrier density and the electric potential computed for a 5 nm thick \( \text{HfO}_2 \) \( (\varepsilon_{\text{rel,static}} = 25 \text{ [38]}) \) layer on top of 5 nm ITO \( (\varepsilon_{\text{rel,static}} = 9.3 \text{ [48]}), \) see Fig. 2(b-c), across which a voltage of 1.5 V was applied. For ITO, we have chosen an effective mass \( m = 0.35m_e \text{ [48]} \) and a low ion density \( n_+ = 1 \cdot 10^{19} \text{ cm}^{-3}. \)
Fig. 3: Carrier density (blue) inside ITO and electric potential (orange) within HfO₂ and ITO upon applying a voltage of 1.5 V across. The electrons inside ITO accumulate exponentially at the interface, which will lead to significant changes in the optical properties.

The resulting carrier distribution clearly shows the expected exponential accumulation and its steep slope will later on give our modulator its special digital characteristic. In many previous discussions the carrier distribution in the ITO has often been averaged across a thin layer around the interface in order to simplify the subsequent discussion. We will further below show the effect on the modulation of the plasmonic signal for both the correct and the averaged carrier distribution.

4. Calculation of Plasmonic Mode Profiles

We now derive the plasmonic mode profiles depending on the carrier distribution in the TCO layer. The modal shape will depend on the local permittivity in the TCO layer. The permittivity however is a function of the carrier distribution. It can be derived once the carrier distribution – as calculated above – is known.

The optical properties – or more precisely the permittivity – of the conducting material change as a function of the carrier distribution. The coupling of the carrier distribution with the permittivity can be described by the Drude model,

$$\varepsilon_r = \varepsilon_\infty - \frac{\omega_p^2}{\omega(\omega + i\gamma)}, \quad (4.1)$$

which provides a sufficient description for the relative permittivity in the NIR. In (4.1), $\varepsilon_\infty$ is the permittivity at infinite frequency, $\omega_p$ the plasma frequency and $\gamma$ the collision frequency. The plasma frequency can directly be linked to the carrier density $n$ via the relationship,

$$\omega_p^2 = \frac{n e^2}{m \varepsilon_0}, \quad (4.2)$$

The parameters of the Drude model depend on the TCO material and on the fabrication processes. We follow [49] and use for ITO the following material parameters $\varepsilon_\infty = 3.9$ and $\gamma = 1.8 \cdot 10^{14}$ rad/s at an optical wavelength $\lambda = 1550$ nm.

The dramatic change of the permittivity at the interface of ITO to HfO₂ when a voltage is applied can be seen from the plots in Fig. 4. The plots were obtained by calculating the carrier distributions for different voltages as described in section 3. Fig. 4(a) shows how the real part of the permittivity crosses zero at the interface to the dielectric, i.e., it is indeed operated in the $\varepsilon$-near-zero (ENZ) regime. ITO is thus transforming from a dielectric-like to a more and more metal-like material in the presence of large carrier accumulation.
Fig. 4: (a) Real part of the permittivity of ITO and HfO$_2$ for voltages between 0.5 V and 3.5 V. At a certain voltage, the permittivity of ITO crosses zero, which is where the strongest modulation will occur due to a strong field enhancement in the ENZ region (shaded). It will be very important that the spatial extent of the permittivity curves with values around ENZ is almost constant for voltages above 1.2 V. (b) Imaginary part of the permittivity of ITO for various voltages. The imaginary part increases at the interface because of free carrier absorption.

The mode profiles of the SPPs in the strongly inhomogeneous material can then be derived by feeding the permittivity from Fig. 4 into a mode solver. For this purpose, we applied again a high order FEM with polynomials of degree 51. This time, the whole structure, c.f. Fig. 2(b-c), from the SiO$_2$ substrate to the Si waveguide and eventually to the top Au electrode was discretized and Dirichlet boundary conditions were applied. First, the transmitting on-state (0 V) was computed to find the fundamental mode which serves as a reference in the mode-finding procedure for the different absorbing off-states. Subsequently, the mode profiles were calculated for situations when a voltage bias was applied.

In Fig. 5, the electric field of the modes is plotted for various bias voltages. We normalized the plasmonic mode with respect to energy to get a fair comparison. The figure shows a zoom-in of the active region since the mode is barely perturbed outside of the carrier accumulation region. We observe for various bias voltages how the absolute value of the z-component of the electric field is influenced by the accumulation of carriers. A sharp field peak can be found once the voltage is above a certain level. We also observe that the strength and the width of the peak remain almost constant when further increasing the voltage.

Fig. 5: Normal component of the electric field in a zoom-in to the active region for applied voltages between 0.5 V and 3.5 V. For a fair comparison, the energy of the plasmonic mode was normalized. We observe that a sharp field maximum is evolving and how its shifts in space. Its position is bound to the zero-crossing of the real part of permittivity and its width by the spatial ENZ range. Hence, the field profiles are not changing significantly anymore above 1.2 V and the modulation will saturate.

For the operation principle of our switch it is now important to understand that a field is strongly enhanced when the permittivity is around zero (i.e. at ENZ). Comparing Fig. 5 with Fig. 4, one can observe that the field peak is approximately located where the real part of the permittivity crosses zero (i.e. at ENZ). This strong field enhancement at ENZ happens exactly in the lossy TCO material which causes the absorption modulation. The limited height and the confinement to a relatively small width of the peak are ultimately responsible for the digital switching behavior. The origin of both
limitations can again be found in Fig. 4. The height of \(|E_z|\) is determined by the continuity of the perpendicular component of the displacement field across the interface. Hence, it depends on the surrounding permittivity. Since the permittivity profile around the zero-crossing is comparable for all voltages above 1.2 V, the peak height remains almost constant and independent of the applied voltage. The peak width is given by the spatial extent of ENZ. It does not increase further since the part of the TCO at ENZ is only shifting above 1.2 V but not growing anymore.

We conclude that the permittivity with values around ENZ is the main cause of our absorption modulation since it leads to a strong field enhancement. The limitation of the spatial extent of ENZ for voltages higher than approximately 1.2 V drives the modulator into saturation. This leads to a flattening of the modulation effect and makes its transfer function digital.

5. Absorption Modulation

The quality of a modulator can be quantitatively described by the extinction ratio (ER) and the on-state propagation loss (PL\(_{\text{on}}\)). A good modulator features a high ER and low PL\(_{\text{on}}\) which both strongly depend on the TCO ion density. The complex propagation constants resulting from the mode computations in section 4 allows us to describe the ER and PL\(_{\text{on}}\) for a certain voltage bias in the case of carrier accumulation.

The propagation loss (PL) is required to determine the ER and PL\(_{\text{on}}\). It is given by the absorption coefficients \(\alpha\) of the respective modes, i.e.,

\[
\text{PL} \text{[dB/\mu m]} = 10 \log_{10} e \cdot \alpha \approx 20 \log_{10} e \cdot 3(\beta).
\]  

(5.1)

where \(\beta\) is the complex propagation constant. The complex propagation constants are retrieved in the mode solver as eigenvalues of the wave equation which belong to the fundamental mode. The PL strongly depends on the carrier density in the TCO before applying a bias, i.e. the ion density \(n_+\), and on the voltage bias. So far, we always assumed a very low ion density \(n_+ = 1 \times 10^{19} \text{ cm}^{-3}\).

Fig. 6(a) shows how the PL depends on the TCO ion density \(n_+\) and the voltage bias. In all cases, we observe a high absorption peak when the TCO material is around ENZ. Furthermore, we see two opposing modulation mechanisms. For low ion densities, the absorption increases with the applied bias, while it decreases with increasing voltage bias for high ion densities. Lastly, Fig. 6(a) shows how the absorption modulation saturates when going to high voltages.

The ER in dB/\(\mu m\) is the difference between the absorption coefficients \(\alpha_{\text{on}}\) of the transmitting on-state and \(\alpha_{\text{off}}\) of the absorbing off-state, i.e.,

\[
\text{ER} \text{[dB/\mu m]} = 10 \log_{10} e \cdot (\alpha_{\text{off}} - \alpha_{\text{on}}) \approx 20 \log_{10} e \cdot 3(\beta_{\text{off}} - \beta_{\text{on}}),
\]  

(5.2)

where \(\beta_{\text{off}}\) and \(\beta_{\text{on}}\) are the complex propagation constants for the absorbing and transmitting state. In Fig. 6(b), we show how the ER changes with the TCO ion density for various bias voltages. We find that the ER increases with increasing doping levels since the spatial ENZ range is getting broader. This is caused by a less steep change of the permittivity when applying a voltage. The ER reaches its first maximum when the whole layer is at ENZ. For higher ion densities, the ER first goes rapidly to a minimum as the layer becomes slightly metallic. At the ER minimum, on- and off-state are swapping from the unbiased to the biased state and vice versa. Above the minimum, the accumulation reduces the field in the TCO since it enhances the metallic properties. Therefore, biasing leads to decreasing losses while the losses in the off-state remain high. This causes another strong increase in the ER until the ion density is so high that the ENZ region is not touched anymore and the ER thus decreases. Hence, by looking only at the ER, it seems to be optimal to start with a rather high ion density at the second maximum. However, this not only makes the device performance very sensitive to the doping level but also comes at the price of relatively high PL\(_{\text{on}}\).

The PL\(_{\text{on}}\) is a measure of the minimum propagation loss in either the biased or the unbiased state of the modulator, i.e., \(\alpha_{\text{on}} = \min(\alpha_{\text{unbiased, biased}})\). In dB/\(\mu m\), it is given by

\[
\text{PL}_{\text{on}} \text{[dB/\mu m]} = 10 \log_{10} e \cdot \alpha_{\text{on}} \approx 20 \log_{10} e \cdot 3\beta_{\text{on}}.
\]  

(5.3)

The PL\(_{\text{on}}\) depends like the ER on the ion density \(n_+\) of the TCO. For a given doping level, it can be extracted from Fig. 6(a) by taking the minimum of the curve for 0 V and the curve with the desired bias voltage.
Fig. 6: Analysis of the performance of a TCO-based absorption modulator depending on the ion density to substantiate the choice of a low ion density of \( n_+ = 1 \cdot 10^{19} \text{cm}^{-3} \). To give the reader an orientation, the areas, where the bulk property of the TCO would show ENZ properties even when no bias is applied, are shaded in grey. (a) Propagation losses (PL) in dB/µm for a range of bias voltages between 0 V and 3.5 V versus ion density (doping level). Two absorption modulation regimes can be distinguished. For weakly doped TCO, the absorption increases with voltage. For high ion densities, it decreases with increasing voltage. Furthermore, the absorption curves are converging for higher voltages which indicates a saturation in the modulation. (b) ER in dB/µm for various biases versus ion density. We find a zero in the ER where the biased state changes from a transmitting on-state to an absorbing off-state and vice versa for the unbiased state. This minimum separates the two aforementioned modulation regions. In the region with small ion densities, the biased state is absorbing because the permittivity leaves ENZ and hence reduces the field in the TCO. (c) FoM of an absorption modulator based on carrier accumulation versus ion density for various biases. Since the PL on is increasing faster than the ER, the best FoM is observed for the relatively low ion densities of \( n_+ = 1 \cdot 10^{19} \text{cm}^{-3} \).

A figure of merit (FoM) should be defined to find a good compromise between ER and PL on. We choose to take the ratio between ER and PL on [4],

\[
\text{FoM} = \frac{\text{ER}}{\text{PL on}} = \frac{\alpha_{\text{off}} - \alpha_{\text{on}}}{\alpha_{\text{on}}}
\]

The resulting FoM for accumulation modulation is depicted in Fig. 6(c). We find the best performance for the lowest possible ion density because the PL on is increasing faster than the ER. Yet, for too low voltages, low carrier densities cannot reach ENZ which significantly reduces the modulation strength.

To reach best performance, we decided for a low initial carrier density \( n_+ \) of \( 1 \cdot 10^{19} \text{cm}^{-3} \) and retrieve a PL on of 0.46 dB/µm and ERs above 1.5 dB/µm. Recalling the field distribution of Fig. 5 and the fact that both peak height and width are limited with applied voltage, we expect that the ER is saturating above 1.5 V. This can be confirmed by plotting the ER or the FoM versus applied voltage as shown in Fig. 7.

Fig. 7: Digital switching can be observed by plotting ER and FoM versus voltage. Two well distinguishable states are found when applying a voltage. If the applied voltage is small the device is transparent, if a larger voltage is applied it is absorbing with an absorption that clearly saturates. The absorption characteristic shows a digital transfer function. Therefore, TCO-based plasmonic absorption modulators are in fact digital plasmonic switches.

Digital switching is found in Fig. 7 since the steep slope and the saturation effect split the ER into two states; a transmitting state below 0.5 V and an absorbing state above 1.2 V. Both of them are quite insensitive to voltage fluctuation which makes the digital operation stable and reliable. Hence,
a TCO-based plasmonic absorption modulator is in truth a digital plasmonic switch. In a practical implementation, a device of 6 µm length, that is forward biased with 1.5 V would provide an ER of 10.2 dB and a PL\textsubscript{on} of 2.8 dB - corresponding to a FoM of 3.7.

6. **Comparison to Existing Models**

A comparison to previous work helps to understand why our results are quite different. TCO-based absorption modulators were already theoretically studied in a large number of publications [4, 7-9, 20-30]. The results presented in these papers mostly rely on an approximation of the optical properties inside the TCO to simplify mode calculations. In more detail, usually either an averaged constant carrier density or an averaged constant permittivity throughout an accumulation layer (ACL) of a few nanometers thickness were assumed although the electrons accumulate exponentially towards the interface. Both simplifications are eventually equivalent and lead to a homogeneously spread ENZ region across the whole ACL. In a next step, when putting these homogeneous material properties into a mode solver one arrives at unphysically high values of the ER due to an overestimated thickness of the ENZ region.

To illustrate the impact of simplifying the accumulation model, we compare the two models under the same circumstances, i.e., we take exactly the same structure, see Fig. 1, and the same material properties. In the inhomogeneous case, we proceed as explained in this work. In the averaged and homogeneous case, we first compute the carrier distribution with the stationary QHD model but then average it such that we have an ACL of 1 - 3 nm thickness where all carriers accumulate while the rest of the TCO remains unaffected. This averaging shows exactly the same absorption characteristics as plate capacitor calculations although the latter case predicts significantly higher voltages to reach strongest modulation. With the obtained carrier density inside the ACL, we get the permittivity via the Drude model and compute the modes and their absorption. While the PL\textsubscript{on} is not affected by the choice of the model, the ER strongly differs as depicted in Fig. 8.

Assuming a homogeneous ACL, one finds strong peaks in the ER around 1.2 V, 2.4 V or 3.7 V for an accumulation layer of 1 nm, 2 nm or 3 nm respectively. Around these voltages, the whole ACL is at ENZ, which causes a field enhancement in an unphysically thick layer. Hence, the maximum ER is strongly overestimated. Furthermore, Fig. 8 emphasizes a certain arbitrariness stemming from the choice of the ACL thickness. This clearly has an unphysical origin and needs to be avoided by using a more accurate description as the QHD model. Assuming an inhomogeneous ACL one finds a lower extinction, yet a digital transfer function.

In conclusion, we find that the assumption of a homogenous ACL leads most likely to overly optimistic absorption modulator values – and is very likely the reason as of why experiments so far did not provide the expected high extinctions.

![Fig. 8: Expected extinction ratios of a device when calculated with the new and more accurate inhomogeneous model and the more established homogenous model. It can be seen that the extinction ratios calculated by a homogeneous model are greatly overestimated and strongly dependent on the assumed ACL thickness. In both models, the carrier accumulation was computed with the stationary QHD model. In the second case, it was averaged over an ACL of 1 – 3 nm. The ACL has homogeneous optical properties, which leads to strong unphysical absorption enhancement in a large area when reaching ENZ. Depending on the assumption of the ACL thickness, both position and strength of the absorption peak are changed drastically. Hence, the results are distorted by an inaccurate assumption on carrier accumulation. Assuming a homogeneous ACL, one finds strong peaks in the ER around 1.2 V, 2.4 V or 3.7 V for an accumulation layer of 1 nm, 2 nm or 3 nm respectively. Around these voltages, the whole ACL is at ENZ, which causes a field enhancement in an unphysically thick layer. Hence, the maximum ER is strongly overestimated. Furthermore, Fig. 8 emphasizes a certain arbitrariness stemming from the choice of the ACL thickness. This clearly has an unphysical origin and needs to be avoided by using a more accurate description as the QHD model. Assuming an inhomogeneous ACL one finds a lower extinction, yet a digital transfer function. In conclusion, we find that the assumption of a homogenous ACL leads most likely to overly optimistic absorption modulator values – and is very likely the reason as of why experiments so far did not provide the expected high extinctions.](image-url)
7. Conclusion

Employing a refined model, the transfer function of TCO-based plasmonic absorption modulators was studied. The simulations predict a digital transfer function with two well-defined states. More precisely, we predict digital absorption modulation by taking advantage of the electro-optical properties of TCOs. In this model, the inhomogeneous carrier distribution in the TCO layers was derived by employing the stationary quantum hydrodynamic (QHD) model, which includes quantum pressure. Feeding the local properties due to the carrier distribution to Maxwell’s equations we then predict the transfer functions of plasmonic absorption modulators. It is found that the spatial ENZ range and the accompanying field enhancement remain almost constant above 1.2 V generating a modulation which is digital. Simulations predict a PLon of 0.46 dB/µm and an ER of 1.7 dB/µm at low voltages of 1.5 V for a hybrid plasmonic waveguide. Such a transfer characteristic would indeed open many new possibilities in integrated optics because it would allow to cascade optical elements without accumulating noise – as transistors in electronics.

8. References


