# Epsilon-Near-Zero Based Electro-Optical and All-Optical Modulator for Intensity and Phase Modulation


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***Abstract*—A modulator based on the epsilon-near-zero effect is proposed to realize intensity and phase modulation, which can work under electrical or optical control.**



***Keywords—epsilon-near-zero, intensity, phase, electro-optical modulator, all-optical modulator***


## I. INTRODUCTION

As an indispensable part of high speed optical network and integrated optical devices, the optical modulator is widely used in optical communication field [1]. The optical modulator has the performance of low loss, high efficiency, ultra-fast response speed and integration size which cannot be achieved by traditional electronic modulators [2][3]. However, the challenges faced by the application of optical modulators mainly come from the materials that compose themselves, including the untunability of materials, narrow spectrum application range, etc., which limit the further development of optical modulators. In recent years, the unique optical properties of epsilon-near-zero (ENZ) materials have brought new opportunities for the development of optical modulators [4][5]. Transparent conducting oxides (TCOs), such as indium tin oxide (ITO) and cadmium oxide (CdO), are typical ENZ materials. ENZ ITO has been widely used in the design of optical modulators. The carrier concentration of CdO can be modulated in the range of $10^{19}$ to $10^{21}$ cm$^{-3}$ under applied voltage modulation [6]. It has been shown that it is beneficial to improve the bandwidth and efficiency of the modulator to replace ITO material which is mostly used in modulator design with CdO with higher mobility [7]. In addition, ENZ CdO also exhibits large nonlinear optical response, low cost, simple manufacturing process, CMOS process compatibility and other characteristics. Current studies on ENZ CdO mainly focus on its electrical properties, but few involve all-optical properties based on nonlinear optical responses, which limit its actual working conditions. This work proposes a tunable electro-optical and all-optical dual-control modulator based on ENZ CdO and its usage method is introduced. Different from the existing optical modulators which can only work under the condition of applied voltage or incident pump light, the dual-control optical modulator in this work can work under both conditions of applied voltage and incident pump light. To the best of our knowledge, this work is the first study to realize intensity modulation and phase modulation [8] in both electro-optical and all-optical working conditions. When operating as an electro-optical modulator, a phase modulation of 26 $\pi$/cm is realized and an extinction ratio of 13 dB/μm can be obtained. When operating as an all-optical modulator, the phase modulation is 25 $\pi$/cm while the extinction ratio is 10 dB/μm. The proposed dual-control optical modulator can work under both conditions of applied voltage and incident pump light, and has the characteristics of low cost, simple production process and tunability, etc., providing a feasible and brand-new scheme for the design of optical modulators.

## II. OPERATION AS AN ELECTRO-OPTICAL MODULATOR

The structure of the proposed modulator is shown in Fig. 1. The width of the CdO nanolayer, cuboid metal electrode, hafnium dioxide ($HfO_2$) nanolayer, silicon (Si) substrate and single groove structure of the electro-optical modulator is 1000 nm in the *y* direction. The thickness of the CdO nanolayer is 15 nm. The cuboid metal electrodes are made of gold (Au) with a length of 15 nm and a thickness of 10 nm. In the past, most metal electrodes were placed on silicon substrates to facilitate better contact between metal electrodes and silicon substrates. This requires the length of the silicon substrate to extend hundreds of nanometers to both sides, which is not conducive to integration. Now the left metal electrode is directly placed on the CdO, which not only reduces the device volume and simplifies the device structure, but also improves the modulation depth by the accumulation of carrier concentration in the metal-oxide-semiconductor capacitor structure driven by the metal electrode. The thickness of the $HfO_2$ layer is 5 nm. The distance between the two parts of the cuboid silicon of the single groove structure is 25 nm in the *x* direction.

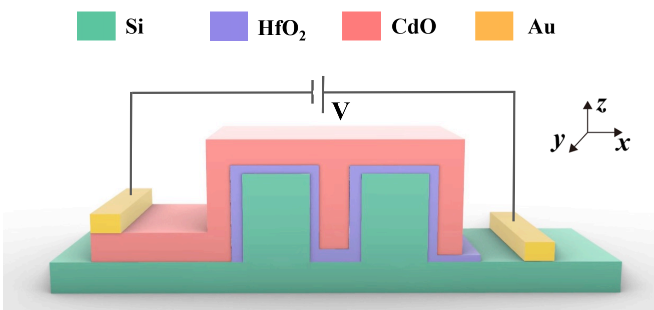


Fig. 1. 3D schematic overview of the proposed structure which is used as an electro-optical modulator.

To investigate the underlying electrical and optical mechanism of electro-optical modulation, the commercial software Lumerical DEVICE Solutions and MODE Solutions are used to simulate the proposed modulator. In the simulation, linearly polarized light with a central wavelength of 1550 nm is coupled to the cross-section of the proposed modulator. When the voltage is applied through the cuboid gold electrode, the carrier concentration of the CdO nanolayer will be changed under the action of the contact potential difference, leading to a change in its complex permittivity and a shift of the ENZ point. When the applied voltage gradually increases, the carriers in CdO accumulate at the boundary of CdO and $HfO_2$, and the concentration increases. Finally, the concentration required to realize the ENZ effect at the communication wavelength is reached, and the optical response also changes correspondingly.

As shown in Fig. 2, the real part of the complex permittivity of CdO decreases with the increase of wavelength, while the imaginary part increases and is greater than zero. When no voltage is applied, the ENZ point of the CdO nanolayer is about 3600 nm. With the increase of the applied voltage, the ENZ point of the thin CdO layer has blue shift. When the voltage reaches 8.8825 V, the ENZ point of the thin CdO layer moves to the communication wavelength of 1550 nm. As shown in Fig. 3, when the applied voltage gradually increases from 0 V, the phase change gradually increases, and the peak value appears at about 8.5 V, achieving a phase modulation of 26 π/cm. With the increase of the applied voltage, the extinction ratio increases accordingly. As shown in Fig. 2 and Fig. 3, when the applied voltage reaches 8.8825 V, the ENZ point of the CdO nanolayer moves to the communication wavelength of 1550 nm, achieving an extinction ratio of 13 dB/μm. Considering the phase change and extinction ratio, the proposed modulator can achieve a fair modulation level by applying 8.5 V applied voltage in this electro-optical working state. Therefore, this modulator achieves intensity modulation and phase modulation under electro-optical control.

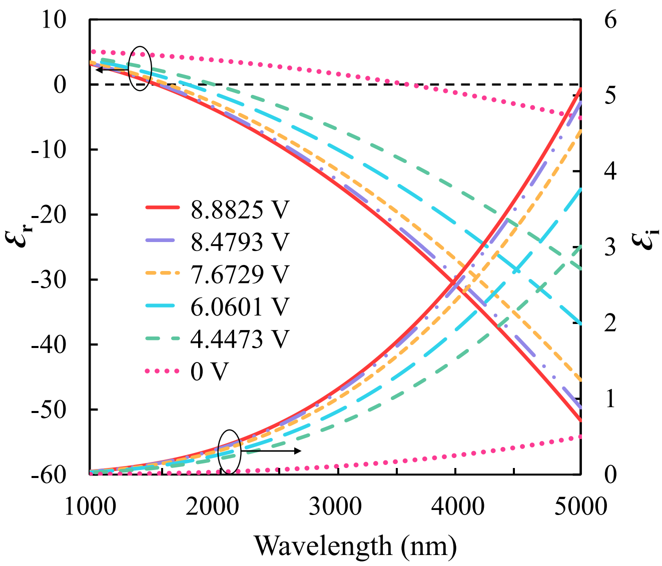


Fig. 2. The variation of the real ($\varepsilon_r$) and imaginary ($\varepsilon_i$) parts of the complex permittivity of CdO, as a function of the wavelength and the applied voltage.

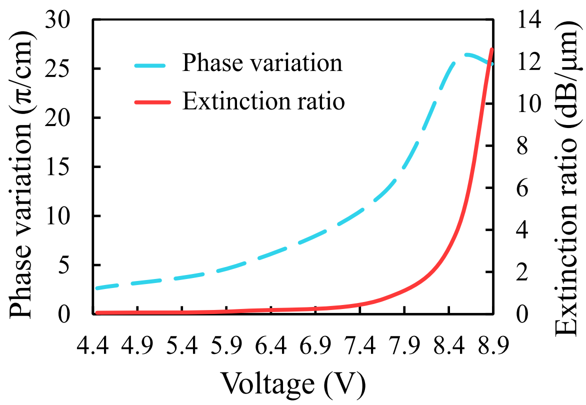


Fig. 3. The phase modulation and variation of extinction ratio of the tunable electro-optical modulator.

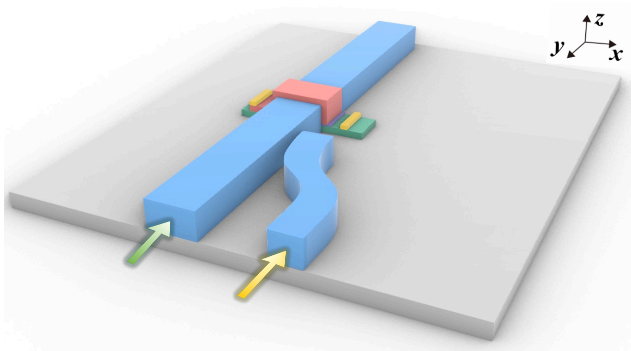


Fig. 4. 3D Schematic overview of the proposed structure which is used as an all-optical modulator. The green arrow represents the probe light while the yellow one represents the pump light.

## III. Operation as an All-Optical Modulator

Due to the huge nonlinear optical characteristic of ENZ CdO, the proposed device can exhibit a large nonlinear response near its ENZ wavelength when the pump light is incident. In this case, the proposed device can be used as an all-optical modulator. Most of the previous all-optical functions are realized in the form of out-of-plane, but here we design a codirectionally coupled waveguide. In the all-optical control mode, the pump light is coupled by a curved silicon waveguide, while the probe light is coupled by a straight silicon waveguide, and both the modulator and the silicon waveguides are placed on the silicon dioxide substrate, as shown in Fig. 4.

Using the two-temperature model (TTM) [9] for calculation and analysis, the effective refractive index $n$, the absorption coefficient $k$, and the increments of $n$ and $k$ of CdO at different pump energy and incident wavelengths can be obtained, as shown in Fig. 5. Under different intensities of pump light, the increase of pump energy will lead to the increase of refractive index $n$ and the decrease of absorption coefficient $k$. At the communication wavelength of 1550 nm, which is also the ENZ region of CdO, $\Delta n$ and $\Delta k$ reach their peak values. In the working process of the modulator, the pump energy has an important effect on its transmission characteristics. The most critical component of the whole device, ENZ CdO, is pumped to generate a huge change of the refractive index, which leads to a performance improvement of the all-optical modulator. Then Lumerical FDTD Solutions is used to analyze the optical field transmission characteristics of the all-optical modulator. As shown in Fig. 6, when the energy intensity of the pump light

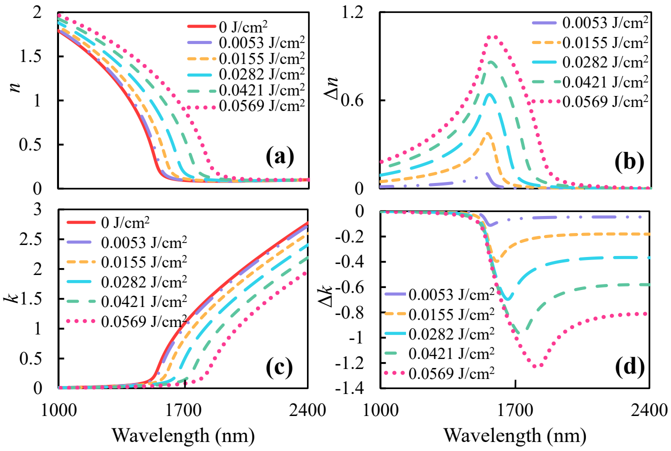


Fig. 5. (a) The refractive index $n$, (b) the changes of refractive index $\Delta n$, (c) the absorption coefficient $k$ and (d) the changes of absorption coefficient $\Delta k$ of CdO at different pump energy and incident wavelengths.

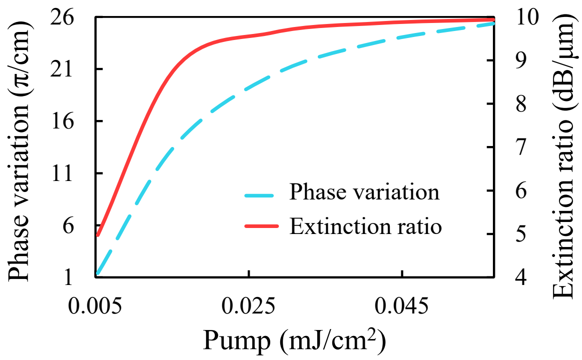


Fig. 6. The phase modulation and variation of extinction ratio of the tunable all-optical modulator.

gradually increases, the phase change and the extinction ratio increase accordingly. When the pump power reaches 0.0569 J/cm$^2$, the phase change increases to a relatively stable value of 25 $\pi$/cm. When the pump power reaches 0.0350 J/cm$^2$, the extinction ratio increases to a relatively stable value at a depth of near 10 dB/μm, which indicates that the performance of the modulator is commendable. Considering the phase change and extinction ratio, the modulator can achieve a fair modulation level by using 0.0569 J/cm$^2$ pump light for all-optical modulation under this working condition. Thus, this modulator achieves intensity and phase modulation under all-optical control.

## IV. Conclusion

In this work, a tunable electro-optical and all-optical dual-control modulator based on ENZ CdO is proposed, and its intensity modulation and phase modulation functions are investigated both electrically and optically. The advantages of the groove structure and the advantages of ENZ materials are combined to obtain high modulation efficiency. When operating as an electro-optical modulator, a phase modulation of 26 $\pi$/cm is realized and an extinction ratio of 13 dB/μm can be obtained. When operating as an all-optical modulator, the phase modulation is 25 $\pi$/cm while the extinction ratio is 10 dB/μm. In this design, the electro-optical and all-optical studies of a single-slot ENZ CdO modulator are carried out, which provides a certain reference for the design of on-chip optical modulators, and could be useful in the development of the on-chip modulators for ultrafast optical communications and signal processing.

## Acknowledgment

This work was supported in part by Guangdong Basic and Applied Basic Research Foundation under Grant 2021A1515012176, in part by Shenzhen Fundamental Research Program under Grant GXWD20201231165807007-20200827130534001, and in part by the Youth Science and Technology Innovation Talent of Guangdong Province under Grant 2019TQ05X227.

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