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A Multi-Parameter Tunable and Compact Plasmon Modulator in the Near-Infrared Spectrum

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Abstract: To keep pace with the demands of modern photonic integration technology, the electro-optic modulator should feature multi-parameter tunable components and a compact size. Here, we propose a hybrid structure that can modulate the multi-parameters of surface plasmon polaritons (SPPs) simultaneously with a compact size by controlling the electron concentration of indium tin oxide (ITO) in the near-infrared spectrum. The length, width and height of the device are only 15 μm , 5 μm and 9 μm , respectively. The numerical results show that when the electron concentration in ITO changes from $7.5 \times 10^{26} \text{ m}^{-3}$ to $9.5 \times 10^{26} \text{ m}^{-3}$, the variation in amplitude, wavelength and phase are 49%, 300 nm and 347° , respectively. The demonstrated structure paves a new way for multi-parameter modulation and the realization of ultracompact modulators.

Keywords: multi-parameter; modulation; electron concentration; near-infrared



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1. Introduction

Manipulating the fundamental characteristics of light, including polarization, wavelength, amplitude and phase, is crucial in modern photonic integration technology [1–4]. The ability to simultaneously control these properties is of great significance and has promising applications in areas such as modulators, sensors and photodetectors [5–8]. For instance, in quadrature amplitude modulation (QAM) schemes, the precise adjustment of signal amplitude and phase is necessary to generate a constellation of points, each corresponding to a unique combination of amplitude and phase [9]. In numerous beam-forming networks, tailored amplitude and phase settings are utilized to activate the individual components of the network [10].

Recently, numerous research has been conducted in the field of multi-parameter modulation to address the growing needs of diverse applications [11–13]. For example, Mohamad’s team has developed four innovative and easy-to-fabricate structures for the creation of high-performance polarization-insensitive modulators that can control both amplitude and phase [14]. Ali Forouzmand’s team has put forward an electrically tunable amplitude and phase modulator, in which the indium tin oxide (ITO) is incorporated into a guided-mode resonance mirror [15]. Nonetheless, despite their advanced merits, these proposed modulators are limited to controlling one or two parameters of light, which significantly impedes their broader application. Our group has reported a plasmon modulator that can control the amplitude, wavelength and phase simultaneously based on a hybrid silicon-dielectric-graphene structure, but it has limited application scenarios as a result of the restricted working wavelength of graphene plasmon [16]. With the development of modern semiconductor materials and photoelectric integration technology,

semiconductors are playing an important role in the field of modern communication systems and integrated circuits [17,18]. The multi-parameter modulation in semiconductors has broad application prospects in fields such as semiconductor chips, lighting equipment and optical storage [19–22]. Thus, it is highly desirable to develop a new method that aims to realize multi-parameter modulation in semiconductors which mainly works in the near-infrared spectrum. Compared with other plasmonic materials in this band, the ITO presents good metal-like optical properties and can be heavily doped. What is more, its electron concentration can be easily modulated by the applied voltage. Herein, the ITO is selected as the alternative material for the plasmon modulator [23].

In this work, a hybrid structure, which can modulate multi-parameters of surface plasmon polaritons (SPPs) simultaneously with a compact footprint by controlling the electron concentration of ITO in the near-infrared spectrum, is proposed and designed. The numerical results show that when the electron concentration in ITO changes from $7.5 \times 10^{26} \text{ m}^{-3}$ to $9.5 \times 10^{26} \text{ m}^{-3}$, the variation in amplitude, wavelength and phase are 49%, 300 nm and 347° , respectively. This scheme paves a new way for multi-parameter modulation and the realization of ultracompact modulators.

2. Model and Simulation

The three-dimensional (3D) schematic diagram of our proposed structure is depicted in Figure 1. The length, width and height of the device are only $15 \mu\text{m}$, $5 \mu\text{m}$ and $9 \mu\text{m}$, respectively. A transverse magnetic (TM) polarized light incidents on the ITO grating, thereby inducing the SPPs to propagate along the surface of the ITO. (The ITO grating is only utilized to compensate for the wave vector mismatch and excite the SPPs because this way has a good excitation efficiency to the SPPs.) The ITO acts as the propagating layer of SPPs. The electron is close to or far away from the surface when the voltage is applied between two silicon substrates. Herein, the electron concentration of ITO can be controlled and yield an obvious change in the refractive index of ITO, and this strong nonlinear effect can improve the modulation performance effectively [24–26] so that the amplitude, wavelength and phase of the SPPs are modulated simultaneously as these parameters strongly depend on the refractive index of ITO. Calcium fluoride (CaF_2) demonstrates superior qualities, including minimal leakage current, strong dielectric strength and a low defect count. Consequently, we have chosen CaF_2 to serve as the dielectric layer, which can significantly enhance the performance of the modulator.

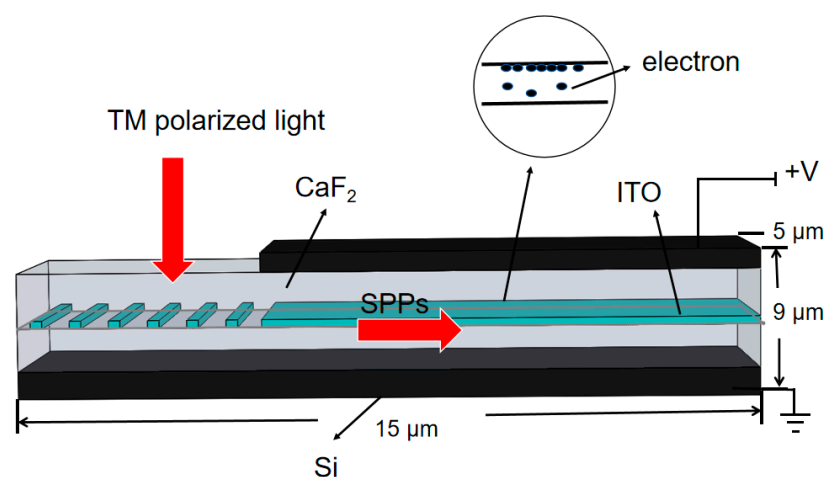


Figure 1. Three-dimensional schematic diagram of multi-parameter joint control modulator.

The conceptualized structure is modeled using the finite element method (FEM), and the two-dimensional (2D) simulation model is displayed in Figure 2. The port mode is employed to stimulate the surface plasmon polaritons (SPPs). (Given that the role of the grating is solely to excite the SPPs, it is deemed superfluous to include the grating in the

simulation as other excitation techniques can also be utilized in this model.) Subsequently, the characteristics of SPPs are examined by varying the electron concentration in ITO. Initially, the electric field distribution and optical transmission are utilized to exhibit the modulation of the amplitude. Then, the alteration of wavelength can be discerned from the distribution of the electric field too. Lastly, the phase distribution within this model also indicates the propagating properties of SPPs. Hence, the amplitude, wavelength and phase of the SPPs can be clearly reflected by the designed simulation model.

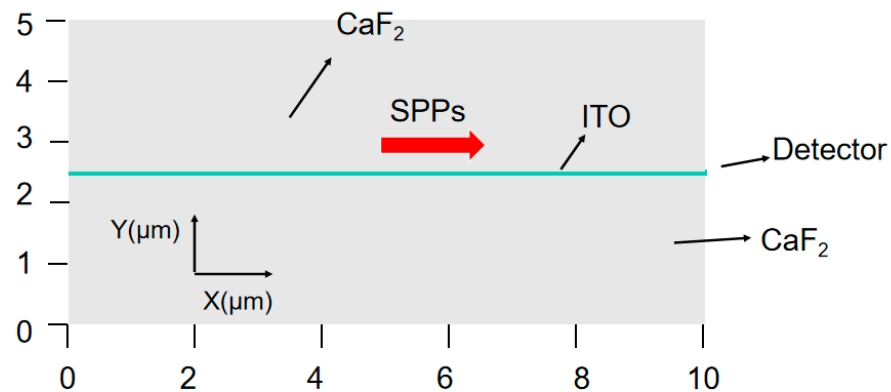


Figure 2. Two-dimensional simulation diagram of multi-parameter tunable modulator.

The dielectric constant is used in the simulation process, and the relationship between plasmon frequency and the dielectric constant can be obtained from Equation (1) [27]:

$$\varepsilon = \varepsilon_{\infty} - \frac{\omega_p^2}{\omega^2 + i\omega\Gamma} \quad (1)$$

where ε_{∞} is the high-frequency dielectric constant, ω is the angular frequency, ω_p is the plasma frequency and Γ is the relaxation frequency. The relationship between plasmon frequency and electron concentration is shown in Equation (2):

$$\omega_p^2 = \frac{Ne^2}{\varepsilon_0 m^*} \quad (2)$$

where N is the electron concentration, e is the electron charge, $\varepsilon_0 = 8.85 \times 10^{-12} \text{ Fm}^{-1}$ is the dielectric constant in the vacuum, $m^* = 0.35 m_0$ is the electron effective mass and $m_0 = 9.1 \times 10^{-31} \text{ kg}$ is the mass of electrons. The relationship between the dielectric constant and the electron concentration can be obtained by combining Equation (1) with (2), and the corresponding real part (n) and the imaginary part (k) of effective refractive index at different electron concentrations can also be calculated. The real part and imaginary part of the ITO refractive index versus the electron concentration are shown in Figures 3a and 3b, respectively, when the wavelength is fixed at $1.55 \mu\text{m}$, which can be utilized in the proposed simulation model.

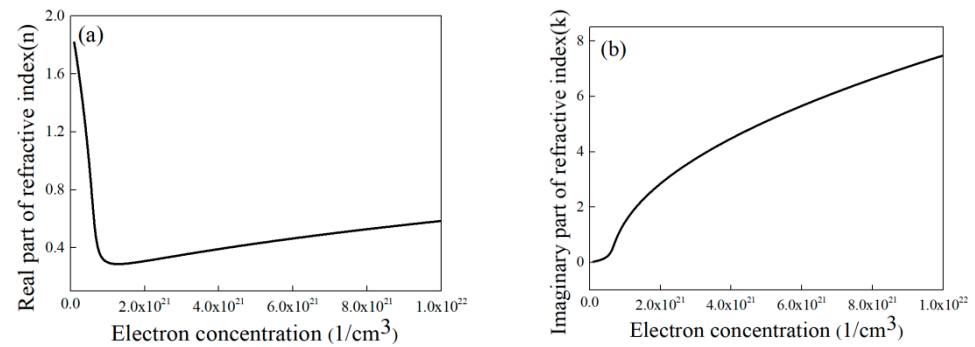


Figure 3. (a) The real part of the ITO refractive index (n) and (b) the imaginary part of the refractive index (k) versus different electron concentrations.

3. Results and Discussion

3.1. Modulation in Propagating Distance

Figure 4 illustrates the y component of the electric field at various electron concentrations with the working wavelength fixed at 1.55 μm . Figure 4a displays the y-component distribution of the electric field at an electron concentration of $7.5 \times 10^{26} \text{ m}^{-3}$, exhibiting a typical attenuation characteristic of SPPs. Figure 4b presents the y-component distribution of the electric field when the electron concentration is raised to $8.5 \times 10^{26} \text{ m}^{-3}$ by increasing the applied voltage. It can be obtained that the SPPs can propagate a longer distance compared with Figure 4a because the propagating SPPs are better localized as the electron concentration increases and the metallic characteristics become more obvious. With the electron concentration continuing to increase to $9.5 \times 10^{26} \text{ m}^{-3}$, the y-component distribution of the electric field is shown in Figure 4c. It can be clearly seen that the propagating distance of SPPs becomes longer, which demonstrates that the proposed model can modulate the propagating distance of SPPs effectively, and the propagating distance changed by 2.7 μm . (The propagating distance is 2.08 μm when the electron concentration is $7.5 \times 10^{26} \text{ m}^{-3}$, while the propagating distance is increased to 4.78 μm when the electron concentration is $9.5 \times 10^{26} \text{ m}^{-3}$.)

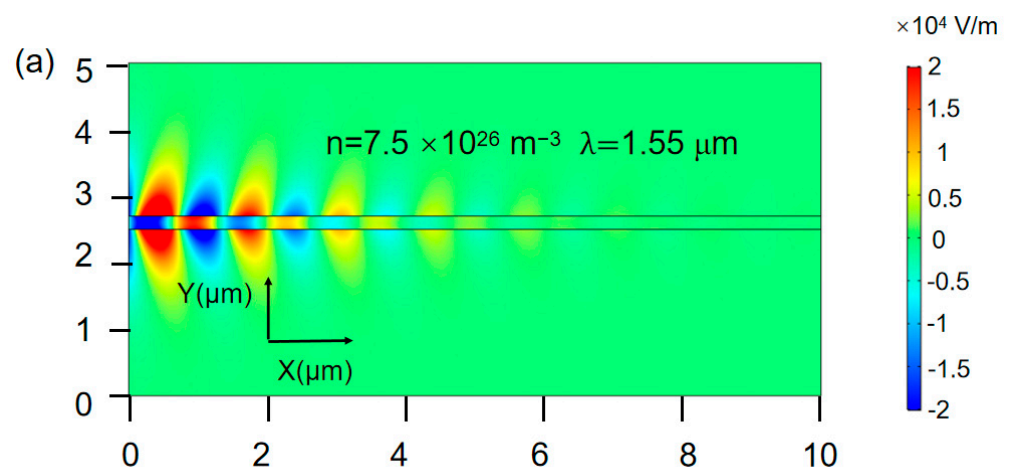


Figure 4. Cont.

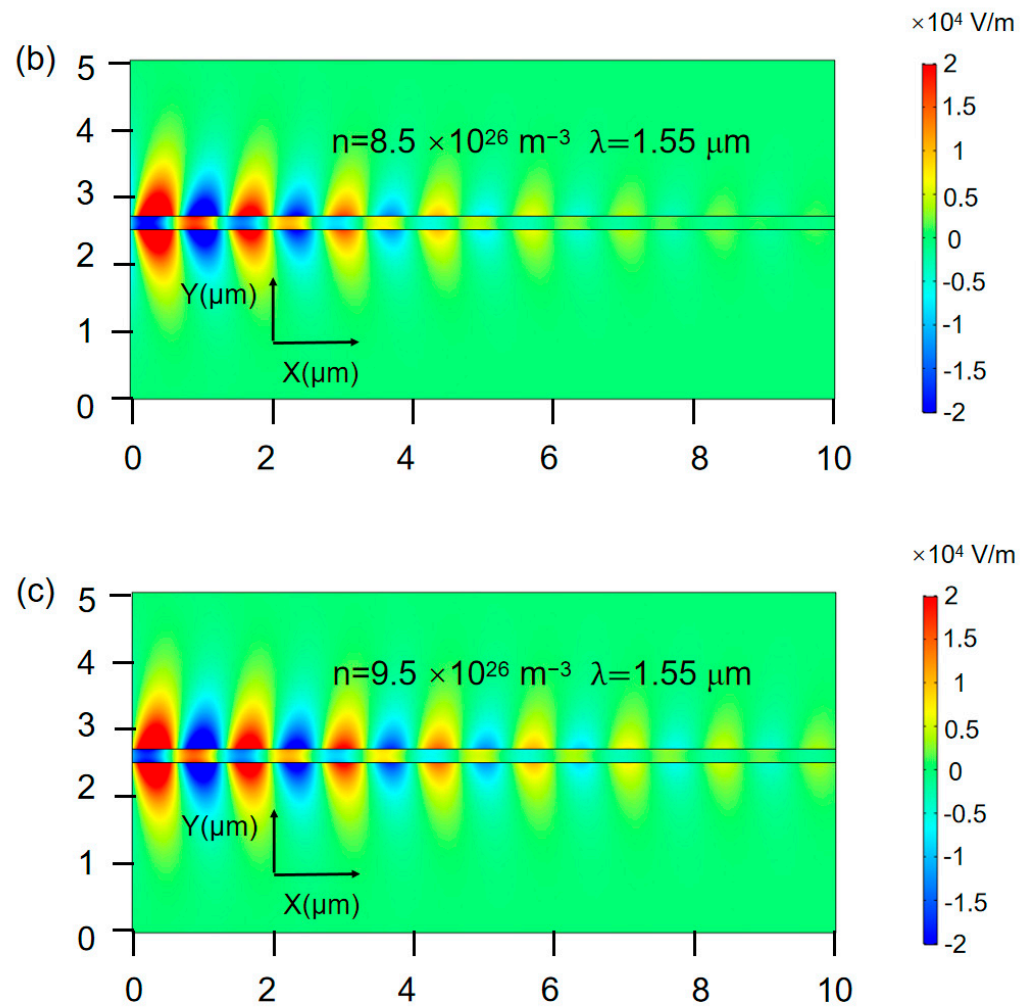


Figure 4. Distribution of y component of electric field intensity with its electron concentration at (a) 7.5 , (b) 8.5 , and (c) $9.5 \times 10^{26} \text{ m}^{-3}$.

3.2. Modulation in Amplitude

Figure 5 illustrates the correlation between the electric field intensity and the electron concentrations. It is observable that the intensity of the second peak in the electric field increases from $1.63 \times 10^4 \text{ V/m}$ to $2.10 \times 10^4 \text{ V/m}$ as the electron concentration rises from $7.5 \times 10^{26} \text{ m}^{-3}$ to $8.5 \times 10^{26} \text{ m}^{-3}$. The electric field strength even reached $2.43 \times 10^4 \text{ V/m}$ when the electron concentration sustainably increased to $9.5 \times 10^{26} \text{ m}^{-3}$, and the electric intensity changed by 49%. It can be demonstrated that the amplitude of SPPs gradually enhances as the electron concentration increases owing to the ITO being of a stronger metallicity leading to the propagating SPPs being localized better and transported a longer distance. Herein, the amplitude of the SPPs is modulated by the proposed model.

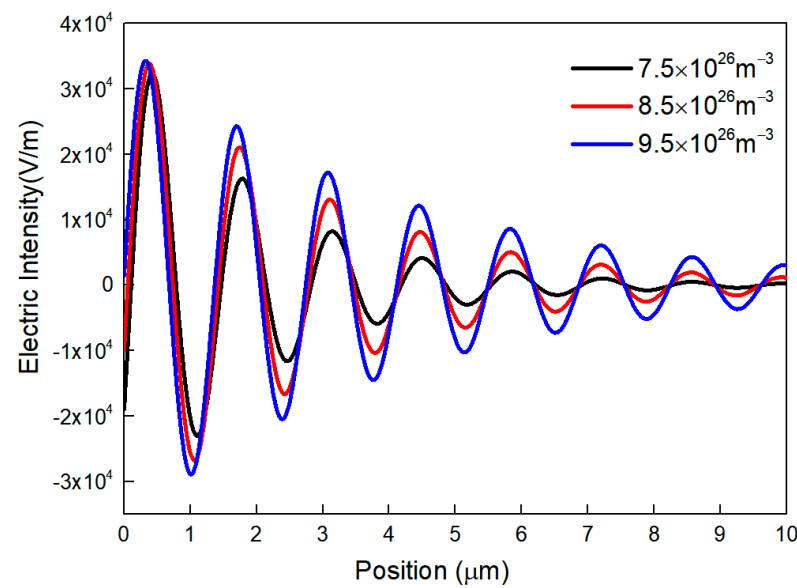


Figure 5. Distribution of electric intensity versus different electron concentrations.

3.3. Modulation in Optical Transmission

Figure 6 demonstrates the relationship between optical transmission and electron concentrations. There is a noticeable enhancement in optical transmission thanks to the reduction in propagation losses when the electron concentration increases. This underscores that our model is capable of modulating the amplitude of the propagating SPPs efficiently by adjusting the electron concentration in ITO. The optical transmission is -75.2 dB (-22.2 dB) when the electron concentration is $7.5 \times 10^{26} \text{ m}^{-3}$ ($9.5 \times 10^{26} \text{ m}^{-3}$). The optical transmission changes by 53 dB.

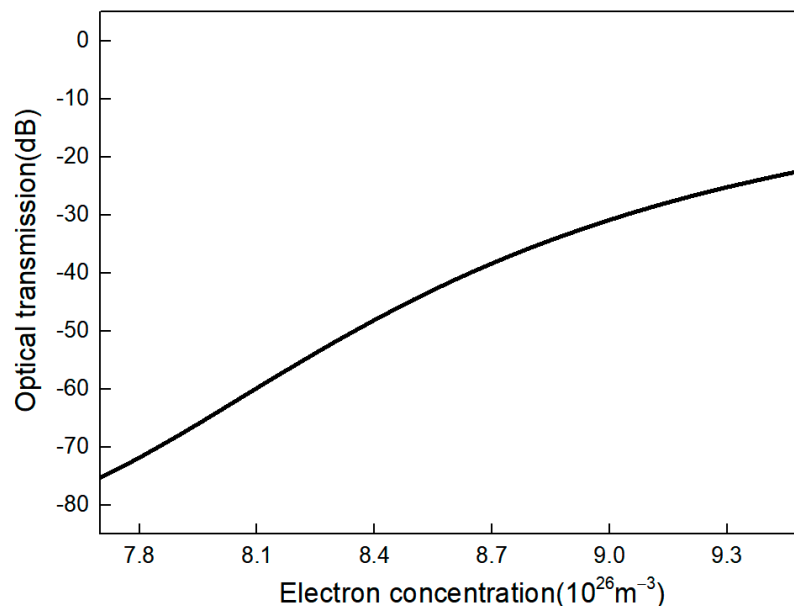


Figure 6. The relationship between optical transmission and the electron concentration of ITO.

3.4. Modulation in Wavelength

Figure 7 depicts the relationship between the wavelength of SPPs and the electron concentration in ITO. It is evident that the wavelength of the SPPs in propagation increases as the electron concentration rises, due to the wavelength of SPPs in ITO being positively correlated with the electron concentration of ITO [28,29]. The wavelength is changed by 300 nm

when the electron concentration of ITO increases from $7.5 \times 10^{26} \text{ m}^{-3}$ to $9.5 \times 10^{26} \text{ m}^{-3}$ (1360 nm at $7.5 \times 10^{26} \text{ m}^{-3}$ while 1660 nm at $9.5 \times 10^{26} \text{ m}^{-3}$). These findings confirm that the wavelength of the SPPs can be effectively modulated by the proposed structure.

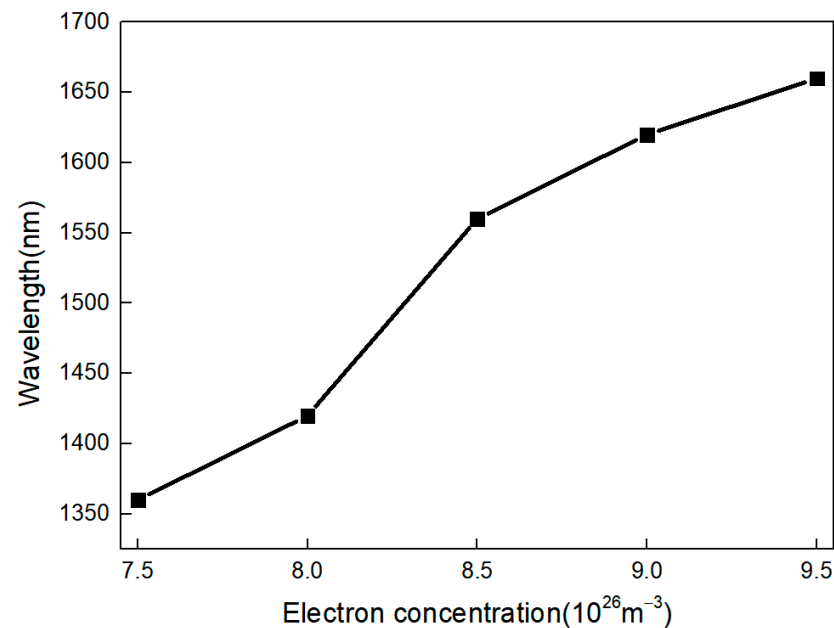


Figure 7. The relationship between the wavelengths of SPPs and electron concentrations.

3.5. Modulation in Phase

Figure 8 illustrates the x component of the phase distribution when the electron concentrations of ITO are $7.5 \times 10^{26} \text{ m}^{-3}$, $8.5 \times 10^{26} \text{ m}^{-3}$ and $9.5 \times 10^{26} \text{ m}^{-3}$, respectively. It is distinctly observable that the phase exhibits varied distributions at different electron concentrations, thereby confirming that our proposed structure can also control the phase of SPPs dynamically. The reason why the phase can be modulated is that the modulation in electron concentration leads to a change in the refractive index of ITO, and the phase of propagating SPPs is strongly associated with the refractive index of ITO as the optical path is changed.

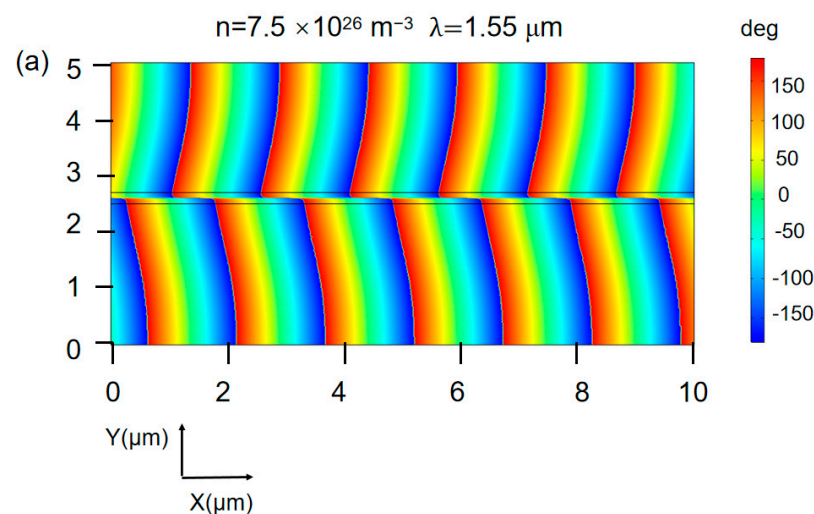


Figure 8. Cont.

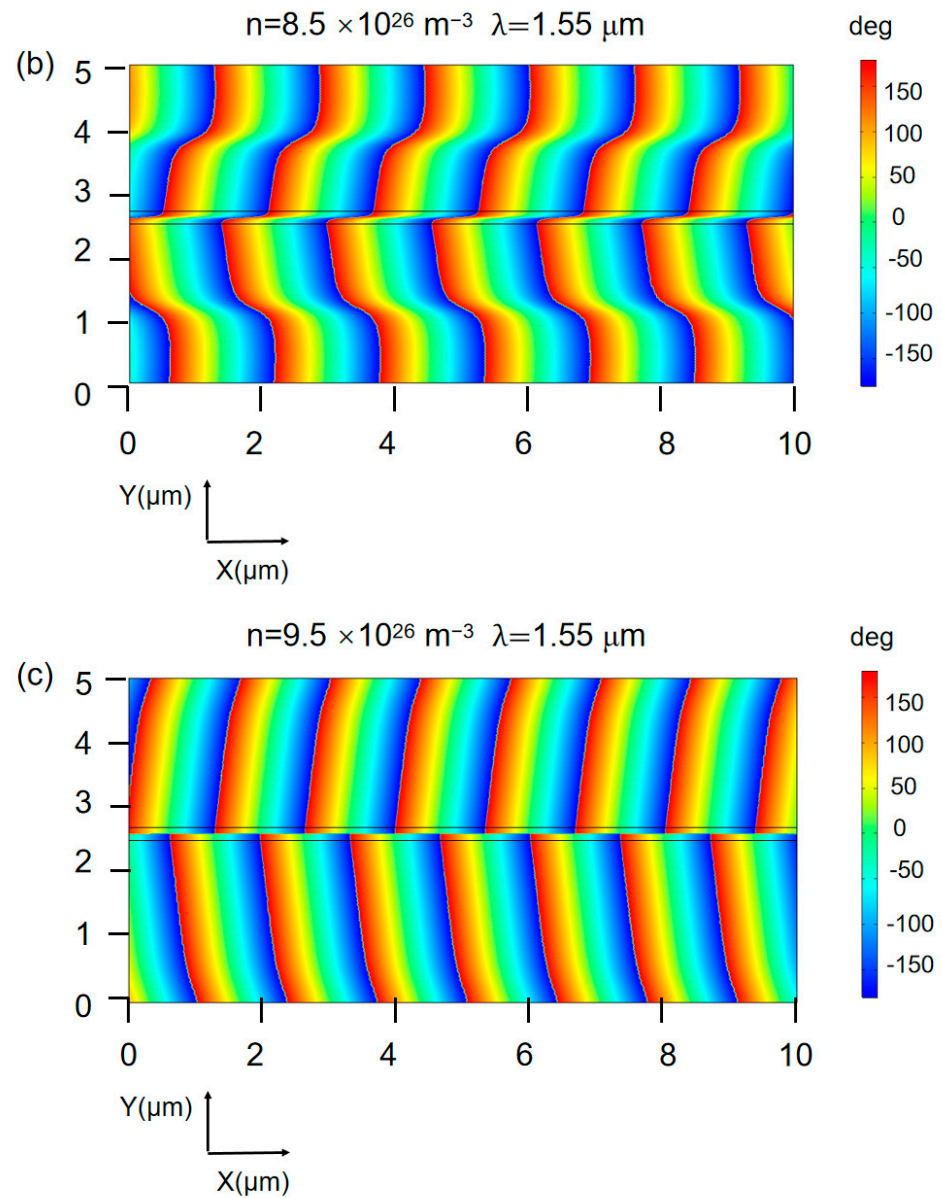


Figure 8. X component of phase distribution under different electron concentrations: (a) 7.5 and (b) 8.5 (c) $9.5 \times 10^{26} \text{ m}^{-3}$.

Figure 9 illustrates the relationship between the phase at the right port and the electron concentrations. The phase angle is 177° at an electron concentration of $8.5 \times 10^{26} \text{ m}^{-3}$. Conversely, the phase angle is -170° at an electron concentration of $9.0 \times 10^{26} \text{ m}^{-3}$, resulting in a phase variation of 347° . This phenomenon occurs because the phase of the propagating SPPs is influenced by the refractive index that is modulated by the electron concentration in ITO.

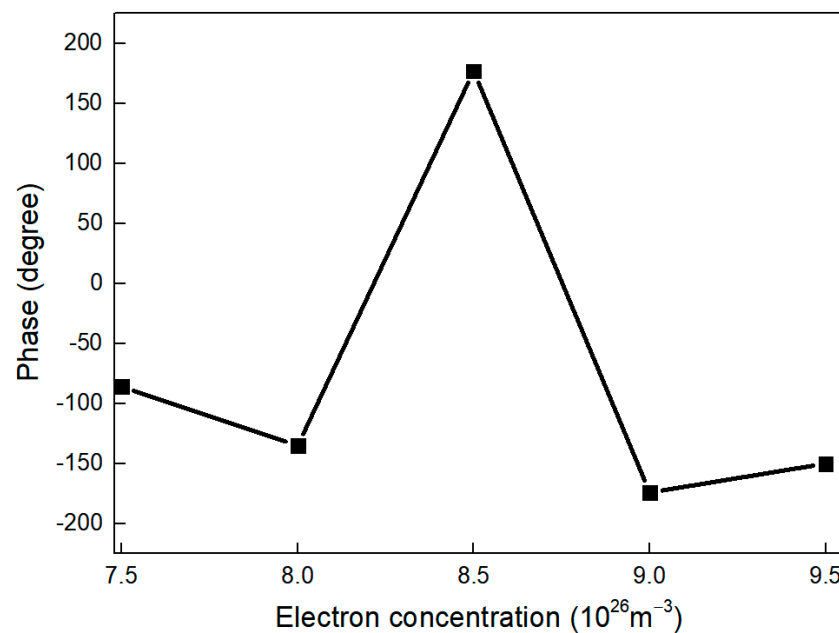


Figure 9. Phase change diagram under different electron concentrations.

4. Conclusions

In conclusion, we have engineered and presented a hybrid silicon-dielectric-ITO configuration, and it can modulate the amplitude, wavelength and phase of SPPs simultaneously with a compact size by manipulating the electron concentration in ITO. The numerical results indicate that a change in the electron concentration of ITO from $7.5 \times 10^{26} \text{ m}^{-3}$ to $9.5 \times 10^{26} \text{ m}^{-3}$ leads to respective modulations of 49% in amplitude, 300 nm in wavelength, and 347° in phase. The capability to achieve multi-parameter modulation of SPPs with a compact size holds great potential for applications in optical communications, sensing and photodetection technologies.

Author Contributions: Conceptualization, X.H.; methodology, C.L.; software, X.Z.; data curation, M.L.; writing—original draft preparation, S.Y.; writing—review and editing, H.W. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The data relative to the experiments discussed in this work are available upon reasonable request from the corresponding author Xuefang Hu.

Conflicts of Interest: Authors Xuefang Hu and Hongfei Wan were employed by the company Ningbo Yongxin Optics Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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