Tunable Electro-Optical Metasurface Based on an Ultra-Strong Coupling Epsilon-Near-Zero System

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Abstract: We demonstrated a tunable electro-optical metasurface based on an ultra-strong coupling epsilon-near-zero indium tin oxide system. The formation mechanism of the Rabi splitting and the performance of the application have been analysed. © 2020 The Author(s)

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1. Introduction

The epsilon-near-zero (ENZ) materials, exhibiting a zero or near-zero permittivity, have been demonstrated extraordinary linear and large nonlinear responses [1, 2]. Indium tin oxide (ITO), one of the ENZ media, has revealed the advantages of low cost, CMOS compatibility, ultrafast optical response and etc. Particularly, the optical properties of the ENZ ITO related to the electron density can be tuned by applying the electrostatic field or optical pumping [1-3], which have become an attractive alternative for integrated photonics. In this work, we propose a design of metasurface with ENZ ITO. The optical response exhibits a strong coupling induced Rabi splitting. And the formation of the ultra-strong coupling system is investigated. Moreover, we provide a promising solution to design a tunable electro-optical modulator based on the ENZ ITO metasurface.

2. Results and Discussions

The designed structure is shown in Fig. 1(a). A cross-shaped array of gold (T_{Au} = 100 nm) and ITO (T_1 = 23 nm), with length, width, and periodicity of W = 50 nm, L = 450 nm, and $P_x = P_y$ = 900 nm, placed on an ITO nanofilm (T_1= 4 nm) and HfO_2 (50 nm). The square ring gold and ITO nanofilm are used as electrodes to apply different voltage V. The complex relative permittivity of ITO can be described by the Drude model. In our study here, the real part of the permittivity is assumed to fall to zero at λ_{ENZ} = 1240 nm [2].

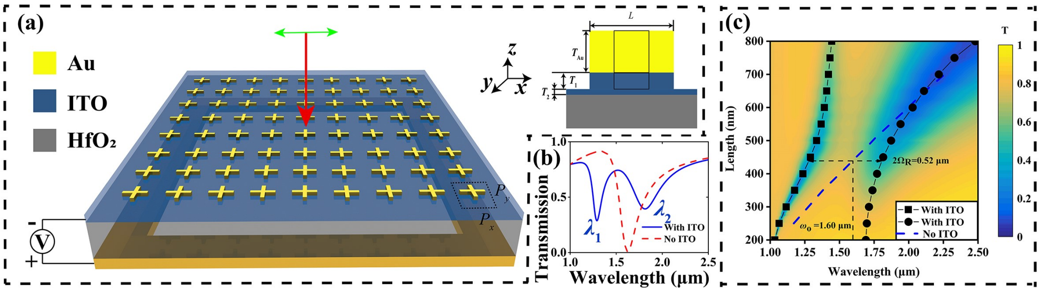

Fig. 1. (a) 3D schematic and the cross-section view of the proposed structure. (b) The transmission of the simple cross-shaped Au metasurface without ITO (the red dashed line) and the ENZ ITO metasurface (the blue solid line). (c) Transmission spectra of the metasurface with ITO as a function of the cross-shaped length, L. The curves with squares and circles represent the positions of the dip at λ_1 and λ_2 of the coupled system, and the blue dashed line represents the plasma resonance wavelength of the bare cavity resonance.

First, we simulated the case of the simple cross-shaped Au metasurface without ITO. In Fig. 1(b), a clear dip occurs in the transmission which is shown as the red dashed line, resulting from the plasma resonance (bare cavity resonance) of the cross-shaped Au excited by the incident light. We also study the influence of the ENZ ITO by introducing the cross-shaped ITO and ITO nanofilm. The blue solid line in Fig. 1(b) displays a Rabi splitting with two dips of different resonance strength at the short-wavelength λ_1 and long-wavelength λ_2, which is markedly different from that of the metasurface without ITO. Figure 1(c) shows the evolution of the transmission of ENZ ITO metasurface as the cross-shaped length L changing from 200 nm to 800 nm. The curves with squares and circles represent the positions of the dip at λ_1 and λ_2. And the blue dashed line in Fig. 1(c) indicates the wavelength of bare cavity resonance. It is obvious that a clear anti-crossing behaviour occurs at curves with squares and circles, which is the main feature of ultra-strong coupling systems [4]. In addition, a minimum Rabi splitting of $2\Omega_R$ = 0.52 μm is observed for the cross-shaped length L = 440 nm, while the bare resonance wavelength ω_0 = 1.60 μm at the same length L. For the coupling system of the designed structure, a normalized coupling rate of (Ω_R/ω_0) = 0.1625.

According to the ultra-strong coupling condition, $\Omega_R/\omega_0 > 0.1$, the designed structure coupling system belongs to the ultra-strong coupling regime [5].

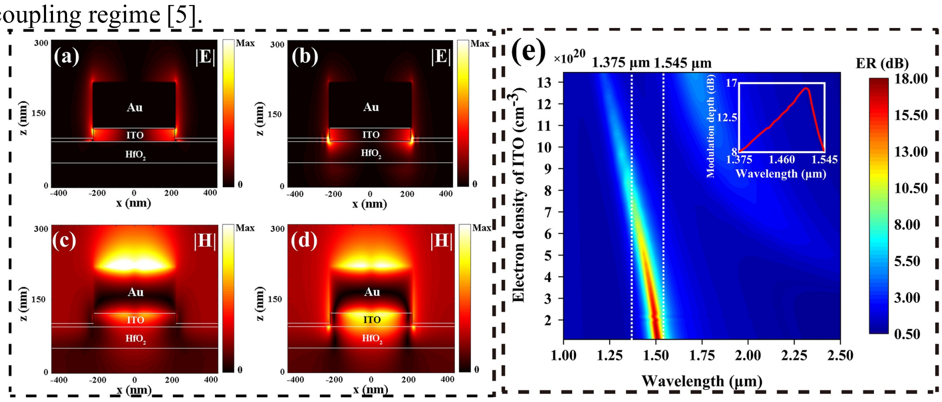

Fig. 2 The field distributions |E| at (a) the short-wavelength dip λ_1, and (b) the long-wavelength dip λ_2. The field distributions |H| at (c) the short-wavelength dip λ_1, and (d) the long-wavelength dip λ_2. (e) The evolution of the tunable electro-optical modulator as a function of the electron density of ITO.

Figures 2(a) and 2(b) presents respectively the field distributions |E| of the coupling system at λ_1 and λ_2. For λ_1, the |E| confined into the ENZ ITO and it abruptly ends at the interface of ITO nanofilm and HfO_2, which suggests the ENZ mode has been excited [6]. However, the field distributions |E| at λ_2 is no longer concentrated in ITO, and it distributes four different regions: the edges of Au, ITO, ITO-HfO_2, and HfO_2-Air interfaces. The result indicating a weak ENZ mode. Figures 2(c) and 2(d) show the field distributions |H| at λ_1 and λ_2, respectively. The |H| filed distribution at λ_1 is locally enhanced in the ITO, which is excited by the gap plasmon resonance. But at λ_2, the |H| filed distribution become more obvious than that of λ_1, due to a strong gap plasmon resonance. The results reveal that the ENZ mode and the gap plasmon resonance play a leading role in the short wavelength dip λ_1 and long-wavelength dip λ_2, respectively, in the ultra-strong coupling system of the designed ENZ ITO metasurface.

The optical properties of the ENZ ITO depending on the electron density of ITO can be easily modulated by applying a bias voltage. When applying to a tunable electro-optical modulator, the extinction ratio (ER) of the designed structure with the changing of the electron density of ITO is investigated. Figure 2(e) shows that, with the decrease of the electron density of ITO, the ER of the short-wavelength dip becomes larger, and the ER of the short-wavelength dip becomes smaller. Besides, the electro-optical modulator can achieve a modulation depth of 8 dB to 16.26 dB from 1.375 μm to 1.545 μm by applying a bias voltage, and the modulation depth can be adjusted by selecting different working wavelengths.

3. Conclusions

We have proposed a tunable electro-optical metasurface based on an ultra-strong coupling ENZ ITO system. The coupling between the ENZ mode and the gap plasmon resonance gives rise to an obvious Rabi splitting. As an potential application, the electro-optical modulator can achieve a maximum modulation depth of 16.26 dB, by changing the electron density of ITO.

Acknowledgments

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