Asia Communications and Photonics Conference 2021 © Optica Publishing Group 2021

Dynamic Epsilon-Near-Zero Wavelength Tuning and Switching Properties of Hyperbolic Metamaterials

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Abstract: We demonstrate the tuning of the epsilon-near-zero wavelength from telecommunication to mid-infrared regime in hyperbolic metamaterials by pump excitation. The structure has a dynamic switching modulation of up to 8.4 dB.

1. Introduction

Epsilon-near-zero (ENZ) materials with a vanishing permittivity have recently been suggested as excellent candidates for nonlinear optics and nanophononics [1,2]. Transparent conducting oxides (TCOs) with advantages of electrically tunable optical properties, large nonlinearity, and CMOS-compatibility have been investigated in many studies such as all-optical switch, modulator, and light-matter interaction [1-4]. The natural ENZ wavelength of TCOs materials can be tuned by applying the electrostatic field or optical pumping. On the other hand, artificial metamaterial composed of alternating layers of metal and dielectric have demonstrated to exhibit ENZ, which is known as the hyperbolic metamaterials (HMMs) [5]. HMMs have a hyperbolic dispersion with a tensor $\varepsilon = [\varepsilon_{xx}, \varepsilon_{yy}, \varepsilon_{zz}]$, where the in-plane component is defined as $\varepsilon_{xx} = \varepsilon_{yy} = \varepsilon_{\parallel}$ and the out-plane component is defined as $\varepsilon_{zz} = \varepsilon_{\perp}$. HMMs have a hyperbolic wave-vector diagram, which can be classified into two types, i.e., Type I ($\varepsilon_{\parallel} > 0$, $\varepsilon_{\perp} < 0$) and Type II ($\varepsilon_{\parallel} < 0$, $\varepsilon_{\perp} > 0$). The ENZ wavelength of HMMs can be designed at specified wavelength by changing the ratio of metal and dielectric. However, their optical responses and ENZ wavelength can only be controlled by the geometry of structures, which limits their applications.

In this work, we design an ENZ hyperbolic metamaterial (HMM) composed of five bilayers of ENZ ITO and SiO_2. The ENZ wavelength of the proposed HMM can be tuned under pump excitation by utilizing the nonlinearity of the ENZ ITO. By the combination of the filling ratio and the pump fluence, ENZ wavelength can be tuned to cover from telecommunication to mid-infrared spectral region. Moreover, the static and dynamic optical responses of HMM have been studied. The results show that the proposed structure has dynamic switching modulation up to 8.4 dB under pump excitation.

2. Tuning ENZ Wavelength of HMM by Pump Excitation

The design of the proposed HMM structure with a thickness of 100 nm is shown in Fig. 1(a), which is composed of five bilayers of ITO and SiO_2. For a multilayer structure, the permittivity can be calculated by effective medium theory (EMT), including the in-plane component $\varepsilon_{\parallel}$ and the out-plane component $\varepsilon_{\perp}$:

$$\varepsilon_{\parallel} = f\varepsilon_{\mathrm{ITO}} + (1-f)\varepsilon_{\mathrm{SiO_2}}, \tag{1}$$

$$\varepsilon_{\perp} = f/\varepsilon_{\mathrm{ITO}} + \varepsilon_{\mathrm{SiO_2}}(1-f)/\varepsilon_{\mathrm{SiO_2}}, \tag{2}$$

where $\varepsilon_{\mathrm{SiO_2}}$ is the permittivity of SiO_2, $\varepsilon_{\mathrm{ITO}}$ is the permittivity of ITO which can be modeled by the Drude formula [6]. $f = d_{\mathrm{ITO}}/(d_{\mathrm{ITO}}+d_{\mathrm{SiO_2}})$ denotes the filling ratio (d_{ITO} and $d_{\mathrm{SiO_2}}$ are the layer thicknesses of ITO and SiO_2). By combining ITO and SiO_2 of different thicknesses, f can vary from 0.1 to 0.9, leading to a shift in ENZ wavelength. From Fig. 1(b) one can observe that the ENZ wavelength can be situated anywhere from telecommunication wavelength to the mid-infrared range with varying filling ratio f. For example, the proposed HMM exhibits an ENZ wavelength at 1550 nm when $f = 0.5$ ($d_{\mathrm{ITO}} = d_{\mathrm{SiO_2}} = 10$ nm), it has a Type I region from 1253 nm to 1520 nm ($\varepsilon_{\parallel} > 0$, $\varepsilon_{\perp} < 0$) and a Type II region at > 1550 nm ($\varepsilon_{\parallel} < 0$, $\varepsilon_{\perp} > 0$), as shown in Fig. 1(c).

The nonlinear optical effect of ITO can be calculated by the non-parabolicity conduction band model [7]. The non-parabolicity conduction band model can obtain the dependence of electron temperature, Fermi level, plasma frequency on the pump fluence. Thus, the permittivity of ITO under different pump fluence can be calculated by inserting the plasma frequency into Drude model. Figure 1(d) depicts the in-plane component $\varepsilon_{\parallel}$ and the out-plane component $\varepsilon_{\perp}$ of the proposed HMM with f = 0.5 at different pump fluence. By increasing the pump fluence, the ENZ wavelength can be tuned from 1550 nm to ~2000 nm, and cause a redshift of Type I and Type II. Furthermore, the Lorentz-resonance pole in the permittivity of the out-plane component $\varepsilon_{\perp}$ is weakened for larger pump fluence.

Figure 1(e) illustrates the ENZ wavelength as a function of pump fluence within 8.6 mJ/cm^2 for different filling ratios. For f = 0.9, the ENZ wavelength can be tuned from 1280 nm to 1792 nm, while f = 0.5 has a range from 1550 nm to 2169 nm and f = 0.1 has a range for 3064 nm to 4381 nm. The results indicate that the proposed HMM structure enables a larger tunable ENZ region covering the telecommunication wavelength to mid-infrared spectral region by designing the filling ratio and the irradiation of pump light. The ability to obtain a large ENZ wavelength range makes these metamaterials a flexible and promising platform for applications in integration.

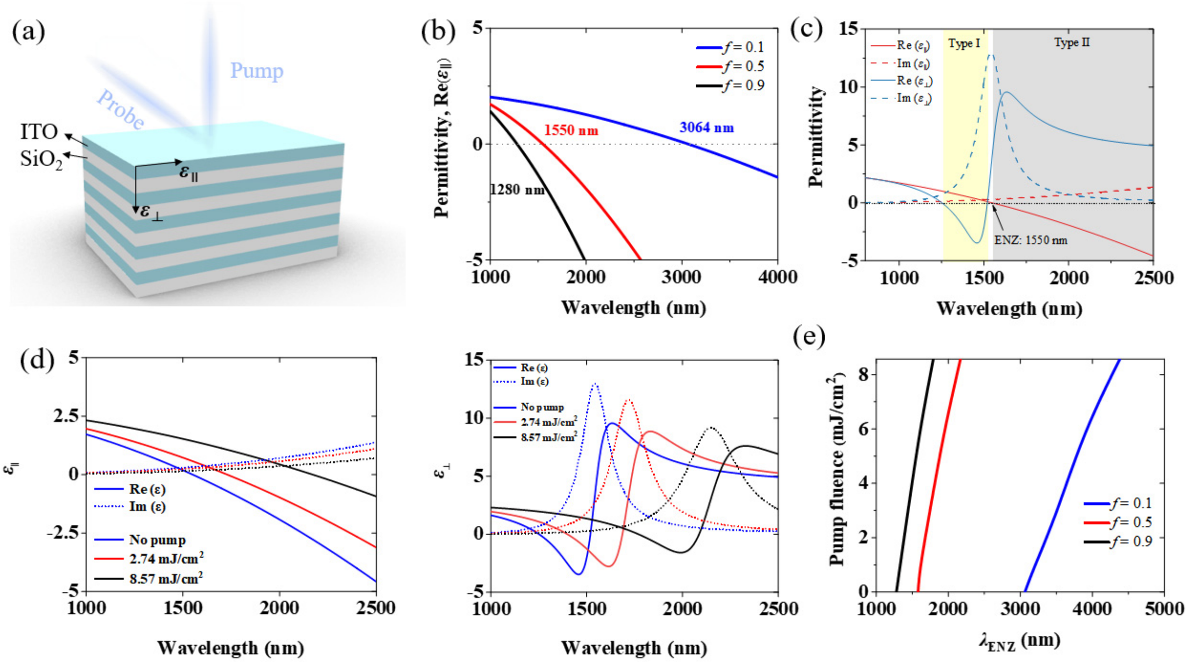

Fig. 1. (a) 3D schematic overview of the proposed HMM structure, the thickness of the structure is 100 nm. (b) Effective permittivity of in-plane component $\varepsilon_{\parallel}$ for different filling ratio f, f = 0.1 represents d_{ITO} = 2 nm and d_{SiO_2} = 18 nm, while f = 0.5 represents d_{ITO} = d_{SiO_2} = 10 nm and f = 0.9 represents d_{ITO} = 18 nm and d_{SiO_2} = 2 nm. (c) Effective permittivity of in-plane component $\varepsilon_{\parallel}$ and the out-plane component $\varepsilon_{\perp}$ of f = 0.5. (d) Effective permittivity of in-plane component $\varepsilon_{\parallel}$ and the out-plane component $\varepsilon_{\perp}$ under different pump fluence. (e) ENZ wavelength as a function of pump fluence for different filling ratio.

3. Static and Dynamic Optical Response of HMM

To explore the static optical response of the proposed HMM structure, firstly the dependence of the extinction of HMM at different incident angles is investigated, as shown in Fig. 2(a). An extinction peak with a nearly fixed spectral location at 1240 nm is observed at oblique incidence angles for p-polarized wave, and becomes larger with the incensement of the incidence angle. The extinction peak can be appreciated by the loss function, which defined as Im($-\varepsilon_{\perp}^{-1}$) [8]. As shown in the subfigure of Fig. 2(a), the calculated result demonstrates that the loss function has a maximum peak at 1240 nm, matching the extinction peak in Fig. 2(a). Therefore, the extinction peak is origin from the resonance occurs in the out-plane component of the permittivity.

As mentioned before, the pump fluence dependence permittivity of ITO can be described by non-parabolicity conduction band model. We explore the switching properties of the proposed structure with the excitation of pump light. Figure 2(b) presents the extinction and loss function under different pump fluence at an incidence angle of 75°. The extinction peak redshifts, broadens and decreases from 7.30 dB to 4.89 dB with the increase of the pump fluence. Additionally, the maximum peak of the loss function is close to the extinction peak, and has a similar trend with the extinction peak, resulting in the resonance absorption of HMM. The switching properties of the proposed structure are presented in Fig. 3(c). The transmission change is defined as $\Delta T/T_0$ = (T - T_0)/T_0, where T is the transmission with pump and T_0 is the linear value (pump off). A large variation in the transmission can be observed at 1260 nm, and reaches up to a maximum of ~350 % corresponding to a larger modulation depth of 8.4 dB. Note that the switching properties of the proposed HMM have the saturated value for pump fluence higher than 5.92 mJ/cm^2. The dynamic switching properties of the proposed structure represent a new paradigm for all-optical switch and modulator.

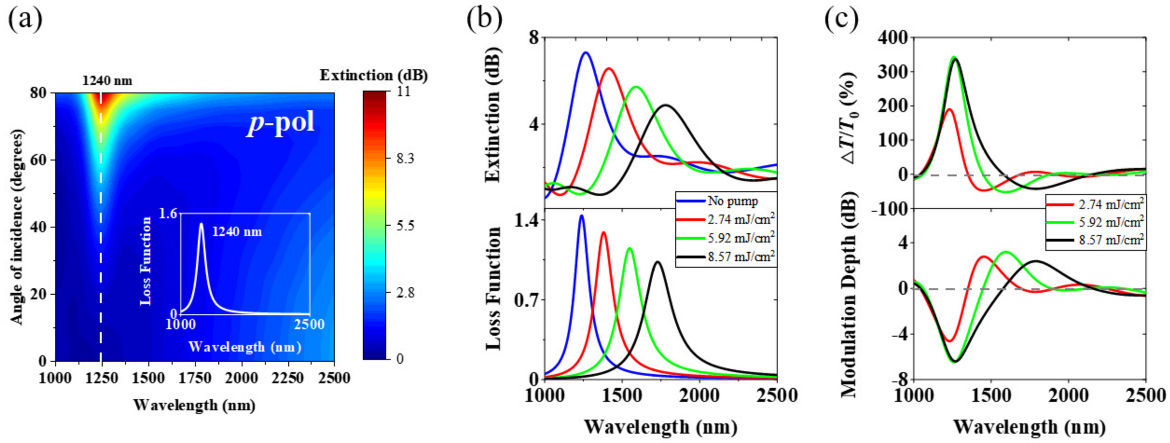

Fig. 2. (a) The evolution of extinction of the proposed HMM structure with $f = 0.5$ as a function of incidence angle. The subfigure is the loss function. (b) Extinction and loss function for the proposed HMM structure under different pump fluence at an incidence angle of 75°. (c) The transmission change and modulation depth for different pump fluence.

4. Conclusions

We demonstrated an ENZ HMM structure composed of five bilayers of ENZ ITO and SiO_2. The optical properties and ENZ wavelength of the proposed HMM can be tuned by pump excitation, with a broad range from telecommunication to mid-infrared spectral region. The loss function indicates that the origin of the extinction peak of HMM. The switching modulation depth of 8.4 dB has been achieved under the pump fluence of 5.92 mJ/cm^2. The results of this work can be very useful in designing ENZ based integrated photonic devices at specified wavelength for telecommunication to mid-infrared spectral region.

Acknowledgments

This work was supported by Guangdong Basic and Applied Basic Research Foundation (No.2021A1515012176), Shenzhen Fundamental Research Program (No.GXWD20201231165807007-20200827130534001) and the Youth Science and Technology Innovation Talent of Guangdong Province (No.2019TQ05X227).

References

[1] J. Wu, Z.T. Xie, Y. Sha, H.Y. Fu, and Q. Li, "Epsilon-near-zero photonics: infinite potentials, " Photonics Res. **9**(8): doc. ID 427246, 2021.

[2] X. Niu, X. Hu, S. Chu, and Q. Gong, "Epsilon-Near-Zero Photonics: A New Platform for Integrated Devices," Adv. Opt. Mater. **6**(10), 1–36 (2018).

[3] Y. Sha, J. Wu, Z. T. Xie, H. Y. Fu, and Q. Li, "Comparison study of multi-slot designs in epsilon-near-zero waveguide-based electro-optical modulators," IEEE Photonics J. **13**(3), 1–9 (2021).

[4] J. Wu, B. A. Malomed, H. Y. Fu, and Q. Li, "Self-interaction of ultrashort pulses in an epsilon-near-zero nonlinear material at the telecom wavelength," Opt. Express **27**(26), 37298 (2019).

[5] P. Huo, S. Zhang, Y. Liang, Y. Lu, and T. Xu, "Hyperbolic Metamaterials and Metasurfaces: Fundamentals and Applications," Adv. Opt. Mater. **7**(14), 1–25 (2019).

[6] M. Z. Alam, I. De Leon, and R. W. Boyd, "Large optical nonlinearity of indium tin oxide in its epsilon-near-zero region," Science **352**(6287), 795–797 (2016)

[7] P. Guo, R. D. Schaller, J. B. Ketterson, and R. P. H. Chang, "Ultrafast switching of tunable infrared plasmons in indium tin oxide nanorod arrays with large absolute amplitude," Nat. Photonics **10**(4), 267–273 (2016).

[8] W. D. Newman, C. L. Cortes, J. Atkinson, S. Pramanik, R. G. Decorby, and Z. Jacob, "Ferrell-berreman modes in plasmonic epsilon-near-zero media," ACS Photonics **2**(1), 2–7 (2015).