Research of an optical device based on an anisotropic epsilon-near-zero metamaterial

Zhibin Wang1 · Qiufan Cheng1 · Xin Li2 · Zhiquan Li1 · Shuhan Meng1

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Abstract
In this work, a novel design of an electro-tunable narrow channel based on an anisotropic epsilon-near-zero metamaterial is presented. The ENZ condition can be flexibly tuned by an applied gate voltage. This permittivity-tunable channel is composed of periodic alternating layers of graphene and nanoglass with a thickness of 3 nm. Additionally, a dual output light modulator is utilized to expand its application. Numerical analysis results show that the maximum transmittance of the incident light can reach 96.7%, and the extinction ratio of the device is 14.8 dB when the gate voltage is added to 4.96 V at the near-infrared wavelength. This ultracompact optical device may open a new realm in highly integrated photonic circuits, especially on the nano-chips.

Keywords Anisotropic epsilon-near-zero (AENZ) metamaterials · Graphene · Nanoglass · Light modulator

1 Introduction
In the past few decades, artificial electromagnetic (EM) metamaterials based on Epsilon-near-zero (ENZ) photonics have attracted widespread attention all over the world (Ioannidis et al. 2020; Askari and Hosseini 2020; Gric and Hess 2017). These materials that do not exist in nature have been proposed and prepared due to their almost arbitrary effective permeability and permittivity. Moreover, these metamaterials have unique optical properties of achieving abnormal regulation of light (Gric, et al. 2018; Tatjana, et al. 2017). The zero-index materials (ZIM), as a specific type of metamaterials, also have become a popular material in scientific research (Hui et al. 2012; Efazat et al. 2020). They are divided into epsilon-near-zero (ENZ) metamaterials, mu-near-zero (MNZ) metamaterials, and matched impedance zero-index metamaterials (MIZIM) (Niu et al. 2018). Because the refractive index of these metamaterials tends to zero, there will be a constant phase advance when the EM wave goes through them. At the same time, there will be other exciting phenomena...
such as the ability to squeeze and tunnel (Silveirinha and Engheta 2006), cloaking (Kundtz and Smith 2010; Papasimakis et al. 2013) and enhanced coupling (Ourir et al. 2013), etc. All the extraordinary optical phenomenon in the ZIMs may guide potential applications on ultra-energy-efficient, all-optical switching devices for future optical communication and computation.

The concept of zero-index material was originated from the proposal of negative refractive index materials by Pendry (2000) and verified by experiments in 2008 (Edwards et al. 2008). By tailoring epsilon to have either a negative or a positive value, the negative refraction, and perfect lenses have been demonstrated (Smith et al. 2004). Up to now, there are many methods to obtain and regulate zero-index materials. For example, Maas et al. (2013) found that a zero-index material can be achieved by a multi-layers material with alternating positive and negative dielectric according to the effective medium theory in 2013. The common one is that silver can be regarded as a material with a negative dielectric constant in the visible spectral range, while silicon is a dielectric with a positive one. Once they were stacked, the two materials construct a zero refractive index material in the visible range. In addition, the regulation of light based on ZIMs has been presented and applied in many fields. For example, Xu et al. found that embedded defects in the zero-index material will affect the reflection and transmission of light (Xu 2011; Wu and Li 2013; Huang and Li 2015). Their results showed that the transmittance of the incident TM wave would be influenced by the sizes, quantities, and permittivity of defects once they are embedded in the zero-index material, which is difficult to change those properties again.

Nanoglass, as a low permittivity material (Reynard et al. 2002), has excellent optical properties. It has a higher light response speed and a giant optical nonlinearity under stable light conditions (Danilov et al. 2016; Wu et al. 2020). Graphene is a two-dimensional material favored by many researchers in optoelectronic research fields over the years, which is composed of a single layer of hexagonally arranged carbon atoms (Falkovsky 2008). Various applications and devices based upon graphene have been widely used in many fields, including antennas (Nair et al. 2008), waveguides (Xu et al. 2018), and switches (Lu 2012) due to the unique electrically tunable optical property of graphene.

Here, inspired by the effective medium theory and the optical property of graphene, an ultracompact epsilon-near-zero metamaterial channel composed of alternating layers of graphene and nanoglass is presented. Only if the permittivity of the proposed channel is tuned to zero value, the incident waves can pass through this waveguide structure in a lower power dissipation under a tunable gate voltage condition. Compared to the defects structure mentioned before, this waveguide structure is more available to realize light modulation. Besides, a dual output light modulator has been illustrated in our work whose characterize is that the output light of two output ports can be arbitrarily selected.

### 2 Design consideration and theoretical model

Figure 1a depicts a straight bend waveguide structure with two parallel Si$_3$N$_4$ waveguides and a graphene–nanoglass metamaterial channel. These two parallel waveguides are connected by the ultracompact channel. The whole structure is sealed by perfect electric conductors (PEC) to prevent the light energy from leaking out. Considering some practical applications based on Ref Yang et al. (2014a), among four sorts of the common metal including Au, Ag, Al, and Cu, we can choose Au instead of PEC to reduce the light propagation loss. The incident wave is input from the left port and output from the right one. The
way of metamaterial composed of alternating layers of graphene and nanoglass has been shown in Fig. 1b. The period thickness of the structure is 3 nm with a 0.6 nm graphene sheet and a 2.4 nm nanoglass layer, and the width of the two Si$_3$N$_4$ waveguides is set as $a_1 = a_2 = 330$ nm whose permittivity is 2.1 (Chen et al. 2009; Anh Pham et al. 2010). Since the width of the Si$_3$N$_4$ waveguides (330 nm) is much smaller than the incident wavelength of 1550 nm, only the fundamental transverse electromagnetic mode can exist in the left waveguides (Emadi et al. 2018; Xiao and Rui 2013). Due to the specificity of our structure, only TM mode can be transmitted through in the z-direction. Therefore, the TM$_0$ mode is selected as the polarization mode to analyze the light distribution of the metamaterial structure in our simulation.

In addition, the transmission coefficient of the structure with two 90° bends is expressed as (Silveirinha and Engheta 2007):

$$ T = \frac{2a_1}{(a_1 + a_2)\cos(k_xd) - i\left(\varepsilon_{yy}\frac{a_1a_2}{a_3} + u_r a_3\right)k_0d\sin(k_xd)} $$

where $k_x = \omega\sqrt{\varepsilon_0\varepsilon_{yy}\mu_0\mu_r}$ is the x-direction component of the wave vector, $\varepsilon_{yy}$ is the vertical direction effective permittivity of the metamaterial, $d$ is the length of the ENZ channel,
and $\mu r = 1$ is the relative permeability of that. According to formula (1), the transmission coefficient can be adjusted to 1 approximately if the corresponding size is designed appropriately due to the loss of the anisotropic ENZ material being neglected. Based on Ref. Yang et al. (2014b), the length of the metamaterial $d$ is better to set to be 15 nm in our structure, which can achieve a large extinction ratio (ER) and an acceptable insertion loss.

In order to design a tunable optical device based on graphene–nanoglass metamaterial, we should first verify the optical properties of the proposed materials. The optical properties of graphene are mainly affected by the electrical conductivity and equivalent permittivity. Hence, tuning the optical property of graphene by changing the gate voltage has been widely used. According to Kubo formulas (Stauber et al. 2008; Efetov and Kim 2010), graphene’s conductivity comprises two parts: the intraband and the interband.

$$\sigma = \sigma_{\text{intra}} + \sigma_{\text{inter}}$$  \hspace{1cm} (2)

$$\sigma_{\text{intra}} = \frac{-ie^2}{\pi\hbar^2(\omega + i2\tau^{-1})} \left[ \int_0^\infty \varepsilon \left( \frac{\partial f_d(\varepsilon)}{\partial \varepsilon} - \frac{\partial f_d(-\varepsilon)}{\partial \varepsilon} \right) d\varepsilon \right]$$  \hspace{1cm} (3)

$$\sigma_{\text{intra}} = \frac{-ie^2(\omega + i2\tau^{-1})}{\pi\hbar^2} \left[ \int_0^\infty \varepsilon \left( \frac{f_d(-\varepsilon) - f_d(\varepsilon)}{(\omega + i2\tau^{-1})^2 - 4(\varepsilon/h)^2} \right) d\varepsilon \right]$$  \hspace{1cm} (4)

where $e$ represents elementary charge ($e = 1.6 \times 10^{-19}$ C), $\omega$ is the angular frequency of the incident wave, $\hbar$ is the reduced Planck constant ($h = \hbar/2\pi$, $h = 6.62 \times 10^{-34}$ J⋅s is the Planck constant), $f_d(\varepsilon)$ is the Fermi–Dirac distribution, and $\tau$ represents the relaxation time which is closely related to the carrier mobility $\mu$ and the chemical potential $\mu c$.

$$f_d = (e^{(\varepsilon - \mu c)/k_B T} + 1)^{-1}$$  \hspace{1cm} (5)

$$\tau = \frac{\mu c}{e\nu F}$$  \hspace{1cm} (6)

where $k_B$ is the Boltzmann constant, $T = 300$ K is the Kelvin temperature ($k_B \cdot T = 0.026$ eV), $\mu$ is set to 1000 cm$^2$/V⋅s, and $\nu F = 1 \times 10^6$ m⋅s$^{-1}$ is the Fermi velocity.

Because the sheet graphene is treated as an extremely thin film, the relationship between the surface permittivity (along the x- and z-directions) of graphene can be expressed as:

$$\varepsilon_{gxx} = \varepsilon_{gzz} = 1 + i \frac{\sigma}{\omega\varepsilon_0\Delta} = 1 - \frac{\text{Im}(\sigma)}{\omega\varepsilon_0\Delta} + i \frac{\text{Re}(\sigma)}{\omega\varepsilon_0\Delta}$$  \hspace{1cm} (7)

where $\varepsilon 0$ is the dielectric constant in vacuum, $\Delta$ represents the thickness of graphene, and we set the thickness of graphene to be 0.6 nm in all the simulations. Considering the normal electric field cannot excite any current in the y-direction, so the normal component of the graphene’s permittivity should be 1. Based on formula (7), we can get the equivalent permittivity of graphene is related to its conductivity and angular frequency. Furthermore, the conductivity will be affected by $\mu c$ which can be controlled by an applied voltage. According to the effective medium theory, the permittivity tensor of this structure can be obtained from Ref. Ding et al. (2013), Zhu et al. (2013):
where \( f_g = 0.2 \) is the filling factor of graphene, \( \varepsilon_d = 1.3 \) is the permittivity of nanoglass (Reynard et al. 2002), \( \eta_0 = 5.65 \times 10^{16} \text{ m}^{-2} \text{ V}^{-1} \), \( V_0 \) is the voltage offset caused by the natural doping (Ao et al. 2014), and \( V_g \) stands for the applied voltage. According to formula (8), the metamaterial’s permittivity tensor along the x and z-direction can be tuned by the chemical potential \( \mu_c \) or the incident wavelength. Based on the formula (9), we can get the vertical direction effective permittivity of the metamaterial is a constant as 1.226. For a given wavelength such as 1550 nm, there is an identical chemical potential \( \mu_c \) corresponding to the ENZ point. All the simulations were investigated by using the commercial software COMSOL Multiphysics based on the finite element method (FEM).

### 3 Results and analysis

Based on the above analysis, we can get the relationship between the equivalent permittivity and the chemical potential of graphene \( \mu_c \). Figure 2a illustrates the horizontal permittivity \( \varepsilon_{xx} \) of the metamaterial as a function of the chemical potential of graphene \( \mu_c \) for a specific incident wavelength (\( \lambda = 1550 \) nm). \( \text{Real}(\varepsilon_{xx}) \) represents the real permittivity of graphene–nanoglass structure (G–N) in our work and \( \text{real}(\varepsilon_{xx2}) \) shows the previous one of graphene–silica structure (G–S) by contrast (Yang et al. 2014b). It can be found that the real part \( \varepsilon_{xx} \) can be changed from a positive value to a negative one with the increasing chemical potential, which demonstrates the real part of permittivity can be tuned nearly equal to zero at a fixed wavelength. Owing to the chemical potential (the Fermi energy level) being higher than the half photon energy (\( \approx 0.4 \text{ eV} \)), the electrons in graphene cannot make the interband transition resulting in the imaginary part of permittivity is always a small value (Klimchitskaya and Mostepanenko 2016).

The results of the simulation are in line with the theoretical predictions. The anisotropic epsilon-near-zero metamaterial can be realized when \( \mu_c = 0.58 \text{ eV} \). Apparently, the ENZ point in our work is around \( \mu_c = 0.58 \text{ eV} \) for \( \lambda = 1550 \text{ nm} \), which is lower than previous work for \( \mu_c = 0.689 \text{ eV} \) (Yang et al. 2014b). That means our work only needs a lower applied voltage to arrive at ENZ condition. In modern electronic communications, the integration of electronic scales often requires nanoscale, and the reduction in device size also requires a further reduction in energy consumption (Kim et al. 2003; Denard 1974), so the reduced 0.109 eV in our structure is particularly important at the aspect of device design in the future. Figure 2b shows that the permittivity of metamaterial is a function of the wavelength of the incident light for a fixed chemical potential (\( \mu_c = 0.58 \text{ eV} \)). The horizontal permittivity of the metamaterial \( \varepsilon_{xx} \) is \(-0.02517 + 0.0083i\) when the incident wavelength is 1550 nm, which is roughly equal to zero value achieving the squeezing and tunneling effect. The distributions of the transverse magnetic field along z-direction for ENZ point of \( \mu_c = 0.58 \text{ eV} \) and non-ENZ point of \( \mu_c = 0.2 \text{ eV} \) are shown in Fig. 2c, d. The light can pass through the structure at ENZ point and get blocked at non-ENZ point, which corresponds
to the ON and OFF states, respectively. Since the chemical potential can be modified by tuning the external voltage, the working wavelength and the permittivity of the proposed light modulator can be controlled by tuning external voltage as well.

Moreover, the transmittance of incident light is shown in Fig. 3. The red bar graph represents the result of graphene–nanoglass structure (G–N) in our work, and the blue one is the graphene-silica structure (G–N) in previous work (Yang et al. 2014b). Considering the

![Figure 2](image-url)

**Fig. 2** a Function of the real and imaginary parts of effective permittivity of the metamaterial in the horizontal direction and the chemical potential of graphene for a fixed wavelength $\lambda = 1550$ nm. The dashed line in the picture represents the previous work of graphene-silica structure. b The relationship between the horizontal permittivity of the metamaterial and various wavelengths of the incident wave for a fixed chemical potential $\mu_c = 0.58$ eV. c and d The magnetic field distribution inside the modulator in the $z$-direction.

![Figure 3](image-url)

**Fig. 3** The transmittance of the two structures against the different chemical potential $\mu_c$ for the fixed incident wavelength $\lambda = 1550$ nm. a The metamaterial is composed of graphene-nanoglass in the structure. b The metamaterial is composed of graphene-silica in the structure.
loss of the ENZ metamaterial, the maximum transmission coefficients of the G-N metamaterial for $\mu \epsilon = 0.58$ eV ($\varepsilon_{xx} = -0.02547 + 0.083i$) is 96.7%, and the one of the G-S metamaterial ($\varepsilon_{xx} = -0.02949 + 0.007i$) is 94.9% (Yang et al. 2014b) for $\mu \epsilon = 0.689$ eV. Based on Eqs. (1) and (9), the transmission coefficient is related to the size of the structure and the vertical direction of effective permittivity of the metamaterial $\epsilon_{yy}$. Concerning the fact that the permittivity of the nanoglass used in the metamaterial is lower than that of silica, the smaller $\epsilon_{yy}$ leads to a greater transmittance (improved about 1.8%), which is consistent with the results obtained in our work. Additionally, the expression of extinction ratio is shown in Eq. (11) from Ref. Soto and Soto (2005), Li et al. (2020):

$$\text{ER} = 10 \log \left( \frac{T_{\text{max}}}{T_{\text{min}}} \right)$$ (11)

$T_{\text{max}}$ and $T_{\text{min}}$ represent the maximum and minimum values of the EM field energy, respectively. It is found that $T_{\text{min}}$ is 0.031 dB corresponding to the OFF state ($\mu \epsilon = 0.2$ eV) and $T_{\text{max}}$ is 0.935 dB is responded to the ON state ($\mu \epsilon = 0.58$ eV), so the extinction ratio (ER) is obtained as 14.8 dB in our structure.

Furthermore, a dual output light modulator designed by this structure has been shown in Fig. 4a. The whole optical device is sealed by PEC as well. We assume that this structure is surrounded by air with permittivity of 1 and the boundaries of the air layer are set as scattering boundary conditions. The size of this channel is the same as we proposed before ($a_1 = a_2 = 330$ nm), and $a_3$ is set to 165 nm after optimization in order to reduce the loss of incident light. The light is input from the bottom port and output from two ports at the top,

![Diagram of the proposed dual output light modulator](image)

**Fig. 4** a Schematic of the proposed dual output light modulator. b and c Magnetic field distributions along the z-direction (Hz) for $\mu \epsilon = 0.2$ eV and $\mu \epsilon = 0.58$ eV, respectively
whose wavelength is 1550 nm. Figure 4b, c demonstrate the magnetic field distribution inside the light modulator in the z-direction.

The result shows that the incident light can pass through the narrow channel and arrives at the outports when the $\mu_c = 0.58$ eV meets the ENZ condition. Otherwise, the light will be blocked at the input port. Due to the structure designed with the advantage on the port selection aspect, this light modulator can freely make the wave pass the two output ports, respectively. By selecting different materials to construct the metamaterial, this modulator also has an important guiding significance in the selection of wavelengths such as the optical splitter. Considering the loss in the shape bends connecting the vertical and horizontal channels (about 20.6%), the energy of the left output is demonstrated in Fig. 5. The maximum energy of one output can be achieved at 31% when $\mu_c$ is enlarged to 0.58 eV. With regard to the symmetry of the T-shaped structure, the maximum energy in our work can be reached about 62% overall.

### 4 Conclusion

In summary, the anisotropic epsilon-near-zero metamaterial channel whose permittivity can be tuned to near zero is designed in this paper. Our work focused on the role of nanoglass, as a low permittivity material, resulting in the device operating at a small applied voltage (reduced about 0.109 eV) and the transmittance of light is increased by 1.8%. And the extinction ratio of the device is obtained as 14.8 dB. The variation of the permittivity is influenced by different chemical potentials $\mu_c$ and different wavelengths. For a fixed wavelength, the channel can be regulated by an applied voltage. In addition, the T-shaped light modulator we designed is very different from the previous work, which is interesting for selective port orientation. The maximum output optical energy of the incident light can be tunneled and regulated at 62%. All the results are essential to optical interconnects and

![Output energy vs. Chemical potential](image-url)

**Fig. 5** The output energy of the left output port under different $\mu_c$
optoelectronic systems, which have potential importance to guide in highly integrated photonic circuits reducing the size of on-chip optical devices.

Authors’ contributions Zhibin Wang, Qiufan Cheng, Xin Li contributed to the conception of the study; Zhibin Wang, Qiufan Cheng, Zhiquan Li contributed to analysis and manuscript preparation; Qiufan Cheng and Shuhan Meng performed the data analyses and wrote the manuscript.

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Availability of data and materials The data sets used or analyzed during the current study are available from the corresponding author on reasonable request.

Code availability Not applicable.

Declarations

Conflict of interest The authors declared that they have no conflicts of interest in this work.

Ethics approval Not applicable.

Consent to participate Informed consent was obtained from all individual participants included in the study.

Consent for publication The participant has consented to the submission of the case report to the journal.

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