Ultra-compact modulator based on Epsilon-Near-Zero metamaterial

Longzhi Yang,[1] Ting Hu,[1] Ao Shen,[1] Chongyang Pei,[1] Bing Yang,[1] Tingge Dai,[1] Hui Yu,[1] Yubo Li,[1] Xiaoqing Jiang,[1] and Jianyi Yang[1,2]

[1]Department of Information Science and Electronics Engineering, Zhejiang University, Hangzhou 310027, China.
[2]Cyrus Tang Center for Sensor Materials and Applications, Zhejiang University, Hangzhou 310027, China

***Abstract*-We present an ultra-compact modulator with a length of 15 nm by utilizing the squeezing and tunneling ability of the Epsilon-Near-Zero metamaterial. The finite-different time-domain simulations show the insertion loss is roughly -0.27 dB while the 3-dB extinction ratio is obtained with a 0.8 V gate voltage. The device's footprint is as small as 0.01 μm^2. This modulator consumes low power and can potentially be ultrafast.**

I. INTRODUCTION

As a fundamental device in the optical communication system, the electro-optical modulator always plays an important role [1]. Since the amplitude and the phase are the basic parameters of the electromagnetic wave, almost all the proposed modulators could be divided into two sorts as the electro-absorptive [2] and electro-refractive ones [3].

The light squeezing and tunneling ability of the ENZ (Epsilon-Near-Zero) material was demonstrated in 2006 [4]. Different from the guide mode theory, the transmission of light in the ENZ channel does not need to be in the form of an eigenmode when analyzed by Faraday's law and Poynting's theorem. Both numerical simulations and experimental verifications for light transmission in the narrow ENZ channels were performed [4,5]. All the former work was based on the non-tunable ENZ material, which limited the usage of this unique property. The light transmission in the narrow ENZ channel can be controlled if a permittivity-tunable material is brought in. The tunable ENZ channel can be designed as a modulator, which belongs to neither the electro-absorptive nor the electro-refractive sort.

Graphene, the two-dimension sheet is a permittivity-tunable material. As a result, we construct a metamaterial as a stack of graphene and silica layers. By applying a proper gate voltage onto the graphene layers, the whole metamaterial shows an ENZ characteristic, which is able to squeeze and transmit the optical energy in the waveguide.

In this work, we present an ultra-compact modulator by using a tunable ENZ metamaterial for the wavelength λ = 1550 nm. The geometrical optimization and modulation effect is shown through computational simulations by using the two dimensional finite-difference time-domain (2-D FDTD) method.

II. DESIGN AND SIMULATION

In Fig. 1 we depict the geometrical structure of the device in a two-dimensional form. Two parallel silicon waveguides are connected with each other by a metamaterial channel. The whole modulator is sealed by the PEC (Perfect Electric Conductor) walls. The light energy inputs from the left port and output from the right one. The metamaterial is composed of alternate layers of graphene and silica as Fig. 1(b) shows. The period of the structure is 2 nm, which is made up of a 0.34 nm graphene flake and a 1.66 nm silica layer. The waveguide's height is set to be $a_1 = a_2 \equiv a$ =340 nm to be identical with the common silicon waveguides. The height of the metamaterial channel is a_{ch} and the thickness is d. The graphene layers can be extended outside to be brought into contact with the metal electrodes.

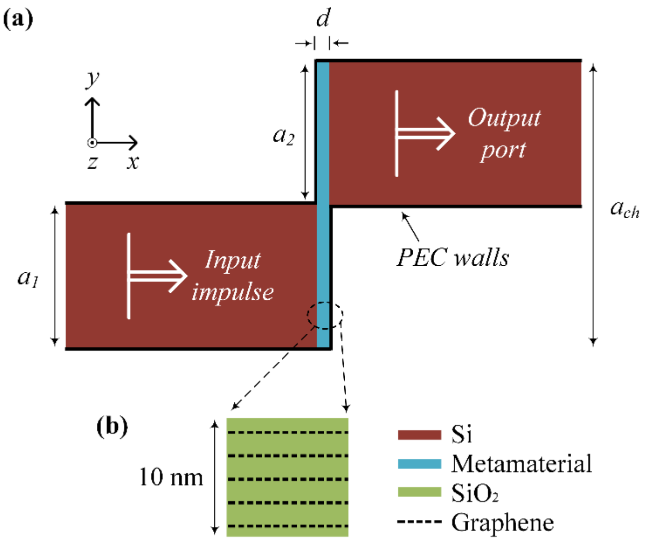

Fig. 1. Illustration of (a) the modulator's structure together with (b) the construction of the metamaterial. The permittivity of silicon and silica are 11.9 and 2.1 in the simulation for the wavelength λ = 1550 nm, respectively.

The surface permittivity of graphene can be expressed by $\varepsilon_{g,xx} = \varepsilon_{g,zz} = 1 + i\sigma/\omega\varepsilon_0\Delta$ and the conductivity σ is related to the graphene's chemical potential μ_c, which is able to be tuned by a gate voltage [3]. The permittivity of the anisotropic metamaterial can be difined by the effectvie medium theory [6].

In order to tunnel the electromagnetic energy through the isotropic ENZ channel, an ultra-narrow channel is necessary [4]. As for an anisotropic and lossy ENZ channel, a seiers of parameters have influence over the transmitting ability [7]. For the proposed device, a large area of the metamaterial section A_p ($A_p = a_{ch} \times d$) induces a large loss of the optical energy, so that we choose the height of the ENZ metamaterial (a_{ch}) to be a small value. On the other hand, the electromagnetic energy inside the input port could penetrate through the metametarial section to the output port if

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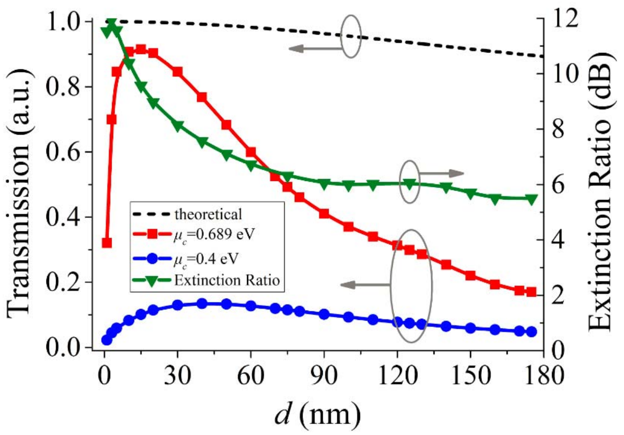

Fig. 2. Optimization of the modulator's geometric structure for the wavelength $\lambda = 1550$ nm. The black dashed line represents the theoretical results. The red and blue lines stand for the simulation results for different graphene's chemical potentials and the extinction ratio between them is shown as the green line.

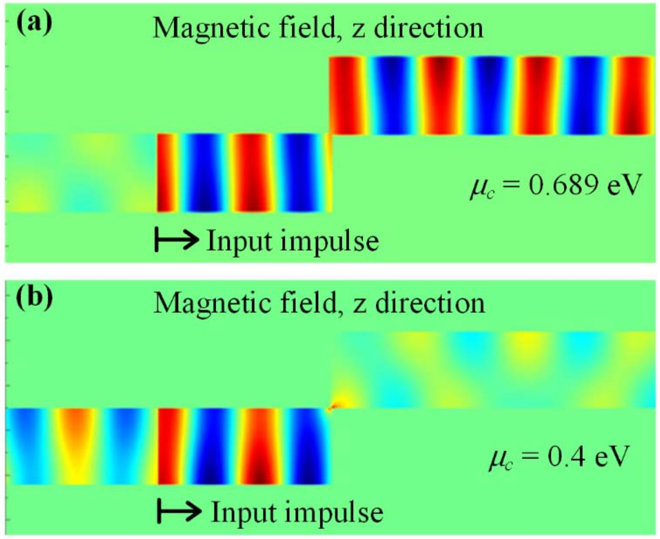

Fig. 3. Modulation effects of the device. (a) and (b) demonstrate the magnetic field distribution inside the modulator in z direction for the ON and OFF status, respectively.

$a_{ch} < a_1 + a_2$. On this condition, the shutoff effect of the modulator would be influenced and the extinction ratio (ER) would be reduced. Consequently, the height of the metametarial section is designed to be $a_{ch} = a_1 + a_2 = 680$ nm. For the purpose of avoiding the light leaking from the metamaterial section, the device is sealed with PEC walls.

As the theoretical analysis predicted, the transmission (T) becomes smaller with an increasing thinkness (d) within the range of $0 < d < 180$ nm. The permittivity of the graphene-silica metamaterial for $\mu_c = 0.689$ eV ($\varepsilon_{xx} = \varepsilon_{zz} = 0.00308 + 0.0102i$, $\varepsilon_{yy} = 1.769$) is utilized into the simulation for different d and the results are shown as the red square line in Fig. 2. The biggest transmission coefficient of the simulation is 0.915 when $d = 15$ nm, which means the insertion loss is -0.27 dB. The ENZ feature is used for the ON status of the modulator. If the permittivity of the metamaterial is not near zero, the light energy can no longer tunnel through the bending channel. The metamaterial for $\mu_c = 0.4$ eV is analyzed for the OFF status. In this condition, $\varepsilon_{xx} = \varepsilon_{zz} = 3.26 + 1.42i$ and ε_{yy} is still equal to 1.769 . The simulation results of the OFF staues are shown as the blue square line in Fig. 2. Hence, the ER between $\mu_c = 0.689$ eV and $\mu_c = 0.4$ eV is able to be presented.

To decrease the insertion loss, d is chosen to be 15 nm. To demonstrate the modulation effect more clearly, the magnetic field in the z direction is shown in Fig. 3(a) and 3(b) for different μ_c. For $\mu_c = 0.689$ eV, nearly all the optical energy is tunneled through the metamaterial channel and output from the right port. For $\mu_c = 0.4$ eV, most of the light is reflected and only a little fraction of energy is squeezed into the metamaterial section. According to our calculation, the modulator obtains a 3-dB extinction ratio with a gate voltage as 0.8 V.

III. CONCLUSION

In conclusion, we have presented an anisotropic graphene-silica metamaterial whose permittivity could be tuned to near zero. The permitivity-tunability of the narrow ENZ channel is utilized to design for a compact modulator with a length of 15 nm. Its insertion loss is -0.27 dB and the footprint is nearly (0.015 × 0.68 ≈) 0.01 μm^2. A gate voltage as 0.8 V is necessary to have a 3-dB extinction ratio. It has the potential to work at an extremly high speed and it may also make contributions to reduce the size of the on-chip optical devices.

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