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Ultra-compact electro-optical graphene-based plasmonic multi-logic gate with high extinction ratio

Mir Hamid Rezaei, Abbas Zarifkar*, Mehdi Miri

Department of Communications and Electronics, School of Electrical and Computer Engineering, Shiraz University, Shiraz, Iran

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ABSTRACT

In this paper, we present a graphene-based plasmonic electro-optical multi-logic gate (MLG) operating at THz frequency. The designed MLG supports AND, XNOR, and NOR logic gates in a graphene-dielectric-metal structure, simultaneously. The propagation length of the surface plasmons (SPs), stimulated by a 27.35 THz incident TM wave, is about 62 times larger in ON state compared to OFF state. Simulation results by the finite difference time domain (FDTD) method show the minimum extinction ratio (ER) of 29.41, 97.38, and 29.40 dB for AND, XNOR, and NOR logic gates, respectively. Also, the minimum modulation depth (MD) is obtained 99.99% for XNOR and 99.88% for AND and NOR logic gates. The proposed MLG provides a high extinction ratio and ultra-compact logical block for using in digital processing circuits and THz applications.

1. Introduction

Due to rapid digital technology advancement, devices with ultra-fast processing capability and high bandwidth are needed. Silicon electronics suffers from limited bandwidth [1,2]. Silicon photonics with high bandwidth, mass-productivity, and fabrication-friendly processes, is a good alternative for silicon electronics [3]. However, the electro-optic effect in silicon is weak and it cannot support high speed digital processing. This drives development of electro-optical devices with new materials and approaches [4].

Plasmonics is a good candidate for integrated circuits since it can extremely confine electromagnetic field at metal-dielectric interface. On the other hand, it has been shown that noble metals such as Au, Ag, etc., cannot support SPs at the THz and far-infrared (FIR) regions [5]. Graphene, as a 2D material, has extraordinary optical and electronic properties which supports SPs at the THz frequency. Relatively low loss, exclusive response to THz waves and above all, the ability of tuning the chemical potential by doping or applying a gate voltage are advantages of graphene [6–10]. Graphene has been used in many active devices such as switches [11,12], modulators [13,14], filters [15,16], logic gates [17], and etc.

Optical logic gates are essential devices for optical signal processing. They have been designed based on many different structures such as photonic crystals [18–20], semiconductor optical amplifiers (SOA's) [21–23], plasmonic waveguides [24–26], and so on. However, the abovementioned structures have their own problems. The logic gates based on photonic crystal structures suffer from extremely large footprint which causes that the size of these structures make the integration process a challenging matter. Logic gates implemented by using cross gain modulation (XGM) and cross phase modulation (XPM) effects in SOA have high power consumption for realization of the nonlinear effects. Also, plasmonic structures using noble metals, cannot stimulate SPs at THz frequencies. Among various designs, electro-optical graphene-based plasmonic logic gates have small footprints and low power consumption and also exhibit flexible tunability. During recent years, several electro-optical logic gates based on graphene-plasmonic structure have been reported. Ooi et al. proposed optical gates with electrical inputs and optical outputs in which to overcome the optional definition of the ON/OFF state in logic gates, coupled graphene sheets in a Mach-Zehnder interferometer (MZI) architecture are used. Since the propagation length of SPs can be driven to the cut-off state, there is a well-defined intensity difference between the ON and OFF states [27].

Yarahmadi et al. presented AND and OR logic gates with two different structures based on graphene plasmonic switch [28]. Realizing logic gates by using constructive and destructive interference between graphene-based plasmonic waveguides has been reported by Wu et al. in Ref. [29]. Unlike two previous researches, the inputs and output are optical and electric voltage is used to control the propagation of light in the waveguides. To date, very few structures have been reported that can support multiple logical operations, simultaneously. The most of previously presented structures support only one logical operation. To perform other logical operations, some alterations such as change of

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* Corresponding author.
E-mail address: zarifkar@shirazu.ac.ir (A. Zarifkar).

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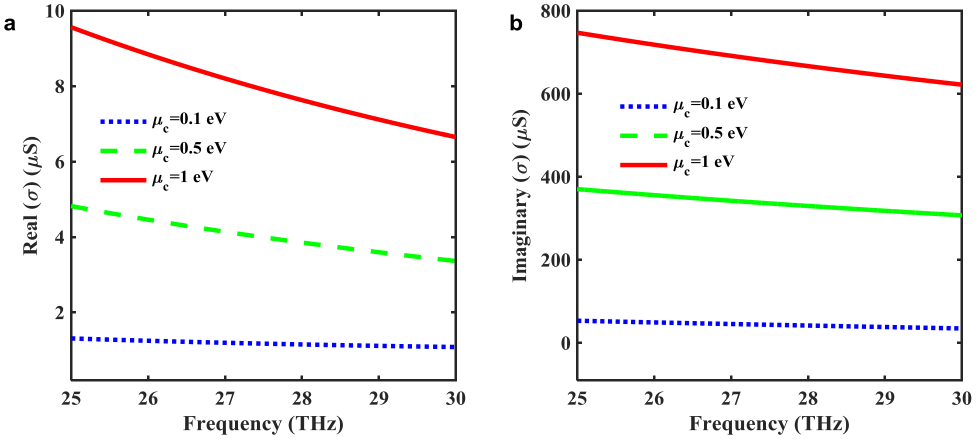

Fig. 1. (a) The real and (b) the imaginary part of the graphene surface conductivity as a function of frequency for different chemical potentials.

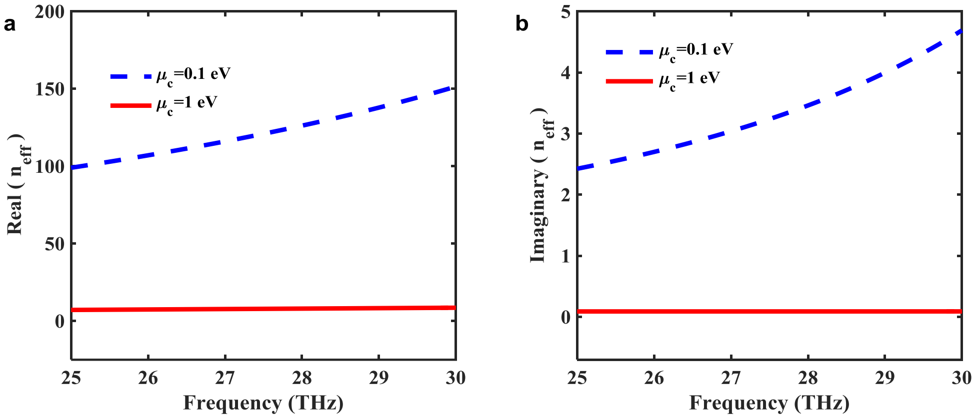

Fig. 2. (a) The real and (b) the imaginary part of the effective index for a graphene sheet surrounded by air (n_m = 1) as a function of frequency for different chemical potentials.

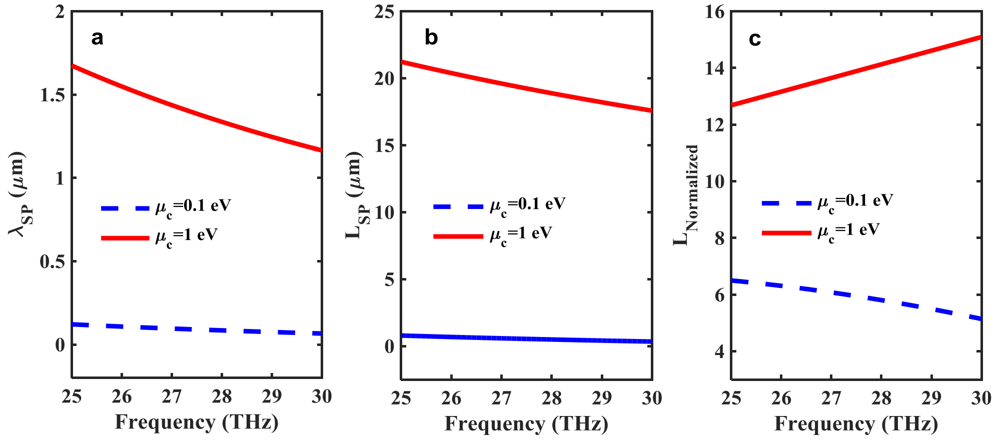

Fig. 3. (a) λ_{SP}, (b) L_{SP}, and (c) $L_{Normalized}$ as a function of frequency for μ_c = 0.1 eV and μ_c = 1 eV.

dimensions, geometric shapes of the structure, phase of the input signals and etc. are required. In this paper, we introduce AND, XNOR, and NOR logic gates based on stimulating SPs in a simple graphene-based plasmonic structure. The designed graphene-dielectric-metal structure with high confinement of light at THz region, has ultra-compact footprint and performs three AND, XNOR, and NOR logical operations, simultaneously.

The rest of the paper is organized as follows. In Section 2, the dispersion relation of SPs in graphene-based plasmonic waveguides is described and the effects of chemical potential changes are investigated. In Section 3, the designed MLG structure is introduced and the basis for its work is described. In Section 4, the simulations results are presented and finally the conclusion is expressed.

2. Graphene-plasmonic principles

The dispersion relation of SPs in graphene can be modeled by theoretical and experimental models such as semi-classical model [30], random phase approximation (RPA) [31], electron energy loss spectroscopy (EELS) [32], and etc. By using semi-classical model, the