# Dynamically tunable Graded Index Photonic Crystal lens based on Dirac semimetal

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***Abstract*-In this paper, we design a graded-index photonic crystal based on Dirac semimetals and simulate the light propagation in the proposed structure using two-dimensional finite-difference time-domain method. The numerical results indicate that the designed GRIN PC has focusing capability for incident light at terahertz frequency range, and its focal distance can be tuned through changing the Fermi energy of the Dirac semimetal.**

## I. INTRODUCTION

Photonic crystals (PCs) are periodic arrays of dielectrics arranged in one- , two- or three-dimensional (1D, 2D or 3D) spaces [1]. The key feature of PCs, i.e., photonic band gap, is caused by modulation of the incident light through spatial distributions of periodic dielectric constants [2]. A recent subset of PCs that have attracted researchers' attention is graded-index (GRIN) PCs. Changes in a) material's refractive index, b) lattice constant, and c) unit cell's filling factor are major known methods to achieve these structures. These methods cause a refractive index gradient in a specific direction; thus, assuming a fixed length for GRIN PC, the structure acts as an optical lens and focuses the incident light on the focal point. The most critical step for designing a GRIN PC is to determine the effective refractive index of the structure's unit cell; therefore, the dispersion diagram is evaluated [3].

In recent years, much attention has been paid to tune the optical properties of GRIN medium to develop dynamic optical devices. With tunable materials, it is possible to control the focal distance (FD) and intensity of the focused light in GRIN PCs. In order to achieve these properties, researchers have investigated a wide range of options, including liquid crystals [4], dielectric elastomers [5] and plasmonic crystals [6]. Recently, there has been much interest in a new unique quantum material known as "Dirac semimetal" due to its high mobility, stability, and ease of manufacture. The dielectric function of these materials can be dynamically controlled with changes in their Fermi energy level by applying a gate voltage; as at lower frequencies than the Fermi energy, metallic response, and at higher frequencies than the Fermi energy, the dielectric response is observed [7], [8]. In this paper, we design a GRIN medium in a PC composed of Dirac semimetal rods with a square arrangement in air background and examine its focusing ability to design a lens. Moreover, we investigate the tuning properties of the FD via changing the Fermi energy of Dirac semimetal.

## II. METHODS

The Dirac semimetal's dielectric function is given by [7]:

$$\varepsilon = \varepsilon_b + \frac{i\sigma_{DS}}{\varepsilon_0 \omega} \tag{1}$$

where $\varepsilon_b$ is the effective background dielectric constant, $\varepsilon_0$ is the permittivity of vacuum, and $\sigma_{DS}$ is the dynamic conductivity of the Dirac semimetal. Real and imaginary parts of $\sigma_{DS}$ in low temperature limit ($T \ll E_F$), is defined by:

$$\mathrm{Re}\,\sigma(\Omega) = \frac{e^2}{\hbar}\frac{gk_F}{24\pi}\Omega\theta(\Omega-2) \tag{2}$$

$$\mathrm{Im}\,\sigma(\Omega) = \frac{e^2}{\hbar}\frac{gk_F}{24\pi^2}\left[\frac{4}{\Omega} - \Omega\ln\left(\frac{4\varepsilon_c^2}{|\Omega^2-4|}\right)\right] \tag{3}$$

where $e$ is the charge of the electron, $g$ is the degeneracy factor, $\hbar$ is the reduced Planck's constant, $E_F$ is the Fermi level, $v_F$ is the Fermi velocity, $E_c$ is the cutoff energy, $\Omega = \hbar\omega / E_F$ is the normalized energy, $\varepsilon_c = E_c / E_F$, and $k_F = E_F / \hbar v_F$ is the Fermi momentum. The AlCuFe is selected as the Dirac semimetal material with the following constants: $\varepsilon_b = 1$ and $g = 40$. In order to design the GRIN structure and investigate its focusing properties, first we study the photonic band structure of the proposed PC which is made of Dirac semimetal rods in air background arranged in a square lattice. Fig. 1 represents the variations of the second band's dispersion diagram for TE polarization as a function of rod's radii at Fermi energy $E_F = 24meV$. It is clear that the frequency dispersion shifts to lower frequencies when the radius of rods increased from 2.4 to $3\,\mu m$. Based on this information, the GRIN PC is designed via changing the radius of rods in a direction perpendicular to that of the light propagation direction. At next step, we calculate the effective refractive index of the second band diagram through $n_g = c(\partial\omega / \partial k)^{-1}$ at different unit cells corresponding to different values of rod radius, shown in Fig. 2 versus the normalized frequency $a/\lambda$. It is obvious that, the effective index diagram has an almost constant steep for each radius in a specific frequency region. Therefore, the discrete effective index values can be obtained from Fig. 2 at normalized frequency of $a/\lambda = 0.265$ within each unit cell in the direction perpendicular to the light propagation. The schematic representation of the designed GRIN PC and the

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corresponding effective index profile are represented in Fig. 3(a) and (b), respectively. The values of effective index obey from $n_{eff}\left(y\right)=n_0\exp^{-\beta|y|}$ function where $\beta=0.0462$ is the gradient coefficient and $n_0=2.095$ is the effective index in the center of the proposed GRIN PC.

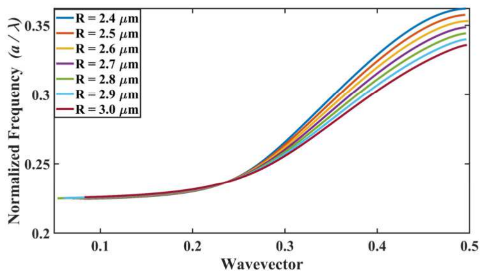


Fig. 1. The second band diagram of 2D PC made of Dirac semimetal rods in air background for TE polarization at different values of rod's radius.

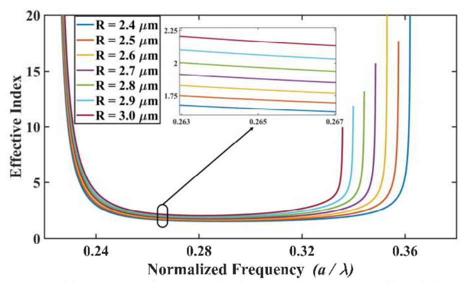


Fig. 2. The effective refractive index versus normalized frequency corresponds to second band diagram at different values of rod's radius.

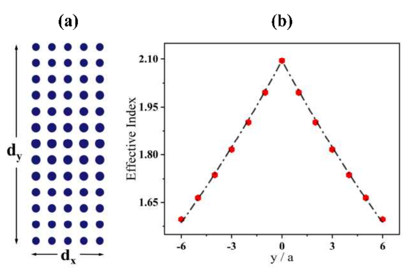


Fig. 3. (a) The schematic representation of the designed GRIN PC and (b) The corresponding effective index profile.

It has been found that the proposed GRIN PC has focusing capability of incident light for width of $d_y=13a$ and length of $d_x=5a$, where $a=10\mu m$ being the lattice constant. To study the focusing properties of the designed GRIN medium, we simulate the propagation of incident TE-polarized light using 2D finite-difference time-domain (FDTD) method. The simulation results for incident normalized frequency of $a/\lambda=0.265$ are shown in Figs. 4(a) and (b) at two distinct values of Dirac semimetal Fermi energy of $E_F=20meV$ and $E_F=24meV$, respectively. The obtained simulation results show that, firstly, the designed GRIN PC lens has focusing behavior, and secondly, the FD of the device can be controlled dynamically through changing the Fermi energy of the Dirac semimetal. Since altering the Fermi energy can change Dirac semimetal's dielectric function, it is expected that the FD of the designed lens can be controlled dynamically. The numerical results for FD are $16.3a$ and $21.5a$, when Fermi energy changes from $E_F=20meV$ to $E_F=24meV$.

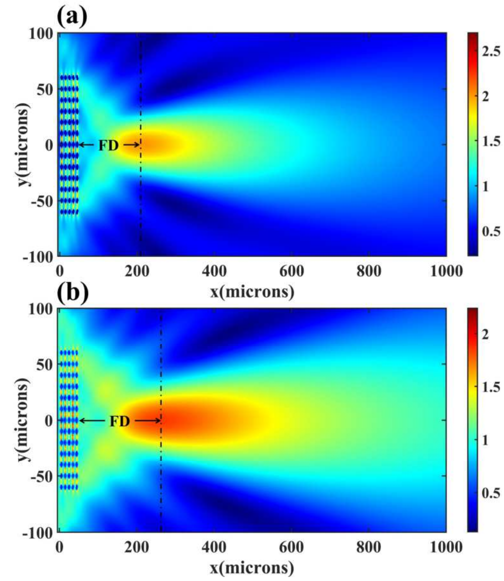


Fig. 4. The electric field intensity distribution of the designed GRIN PC with $d_x=5a$ and $d_y=13a$ for TE-polarized incident normalized frequency $a/\lambda=0.265$ at two distinct values of (a) $E_F=20meV$ and (b) $E_F=24meV$.

## III. Results

In this paper, we designed a GRIN PC composed of Dirac semimetal in air background and studied its focusing properties, as well as, its focal length tunability by changing the Fermi energy of Dirac semimetal. The numerical results indicate that the deigned GRIN medium behave like a lens with tunable focal length. Therefore, dynamic control of light propagation in a GRIN PC structure based on Dirac semimetal could have the potential to be utilized as a tunable electro-optic lens.

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