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Design and characterization of graphene ultra-thin flat lenses

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Abstract— A **Fresnel zone plate is a flat and compact lens. This paper reports research into Fresnel zone plate constructed using graphene rings. The tunable lensing effect of the lenses was designed and analysed using FDTD method. Then graphene Fresnel zone plate array were fabricated with CVD and photolithography processes. The effect of the lenses was characterized under optical microscope. The experimental results demonstrate that the flat lenses with graphene rings have the ability to focus light with high contrast. The research demonstrates that graphene rings can work in Fresnel zone plates. The optical property of the graphene rings can be tuned by voltage and thus the focal intensity.**

Keywords— Graphene, thin lenses, tunable, Fresnel zone plate

I. Introduction

Properties of graphene, like being one atomic layer thick, highly conductivity, transparency, and strength, make it a credible candidate for a myriad of applications, such as touch screens, displays devices, solar cells, photo-detectors, etc. In this research we explore a novel application of using graphene to produce the thinnest possible tuneable optical lenses.

Optical lenses are usually constructed by curved surfaces and they focus light by bending it across the curved surface profile. However, there is a great need for producing compact, light and thin optical lenses for applications where space is a vital factor. Also flat lenses take the advantages of being aberration free as compared to curved surface lenses.

Fresnel zone plates are a type of flat lenses, which are formed by a set of concentric rings, alternating between transparent and opaque. By introducing abrupt changes of the phase of light, which breaks the dependence on the propagation effect, Fresnel zone plates offers the possibility of designing high numerical aperture (NA) lens with low weight and volume. It has been widely used in various applications, such as optical interconnects[1] , beam focusing[2, 3], and integrated optics[4].

In this paper, graphene is used to make the opaque zones of Fresnel zone plates to explore the thinnest possible lens for compact optical system. Although monolayer graphene is almost transparent, for N layers graphene the absorption increases with the layers, and the transmittance could be written as [5]: $T \cong 1 - N\pi\alpha$. So it is possible to make the opaque zones with multi-layer graphene.

Through computational modelling by FDTD method, the tuneable properties of the graphene Fresnel lens under light of wavelength of 850 nm, which is one of the important windows in optical communication, are studied. The simulation results show very clear tunable lensing effect of graphene lens. Then graphene Fresnel zone plate array were fabricated by photolithography method. Characterization using microscope shows that these arrays have the ability of focusing light with high contrast, which means that these graphene Fresnel zone plates work. The research confirms the possibility of making tuneable ultra-thin lens with graphene.

II. Computational Modelling

A. *Properties of Graphene*

The surface conductivity of graphene can be obtained from the Kubo formula for finite temperatures T, written as[6]:

$$\sigma = \frac{e^2(\omega + i\tau^{-1})}{i\pi\hbar^2}\left[\frac{1}{(\omega + i\tau^{-1})^2}\int_0^\infty \varepsilon\left(\frac{\partial F(\varepsilon)}{\partial\varepsilon} - \frac{\partial F(-\varepsilon)}{\partial\varepsilon}\right)d\varepsilon - \int_0^\infty \frac{F(-\varepsilon) - F(\varepsilon)}{(\omega + i\tau^{-1})^2 - 4\left(\frac{\varepsilon}{\hbar}\right)^2}d\varepsilon\right]$$
$$= \sigma^{intra} + \sigma^{inter} \qquad (1)$$

in which $F(\varepsilon) = \{1 + \exp[(\varepsilon - \mu_c)/K_B T]^{-1}$ is the Fermi Dirac distribution with μ_c the chemical potential; K_B is the Boltzmann constant; $\boldsymbol{\omega}$ is the radian frequency; τ is a phenomenological electron relaxation time, which could be obtained from $\tau = \mu\mu_c/(ev_F^2)$; μ= 10000 cm^2 / (Vs) is the measured dc mobility, and e is the electron charge and υ_F= 1 × 10^6 m / s is the Fermi velocity[7].

In the Eq. (1), the first term arises from contributions of intraband electron-photon scattering and the second term corresponds to interband electron transitions. When $\mu_c >> K_B T$ (for room temperature, $K_B T$~26 meV << μ_c), Equation (1) could be simplified as:

$$\sigma = \frac{ie^2\mu_c}{\pi\hbar^2\,(\omega + i\tau^{-1})} + \frac{e^2}{4\hbar}\left[1 + \frac{i}{\pi}\ln\frac{\hbar(\omega + i\tau^{-1}) - 2\mu_c}{\hbar(\omega + i\tau^{-1}) + 2\mu_c}\right] \qquad (2)$$
$$(\mu_c \gg K_B T)$$

In the simulation, the volume conductivity is calculated by $\sigma_V = \sigma_S/\Delta$, where Δ= *N*tg is the thickness of N-layer graphene and tg=0.34 nm is the monolayer graphene thickness. As graphene is highly anisotropic, only the in-plane component is treated as dispersive. The graphene layer is put in XZ plane

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and light comes from y direction, then the permittivity of graphene could be expressed as[8] :

$$\varepsilon_{xx} = \varepsilon_{zz} = \varepsilon_r + \frac{i\sigma_v}{\varepsilon_0\omega} = \varepsilon_r + \frac{i\sigma_s}{\varepsilon_0\omega\Delta} \tag{3}$$

$$\varepsilon_{yy} = \varepsilon_r \tag{4}$$

where $\boldsymbol{\varepsilon}_0$ is the vacuum permittivity and the dielectric permittivity $\varepsilon_r = 2.5$.[9]

The permittivity of 5-layer and 10-layer graphene was studied under the light of 850nm wavelength, as shown in Figure 1. For different layers, graphene has the real permittivity peaks at the same Fermi level, 0.73eV, at which position the imaginary part of permittivity appear a sharp edge. Compared with 5-layer graphene, 10-layer graphene has lower peak real permittivity, as well as lower imaginary permittivity before the sharp edge. When the Fermi level is larger than 0.73eV, the imaginary permittivity is almost zero no matter how many layers. The study indicates that permittivity can be changed by Fermi level, which could be used to make the lens tuneable.

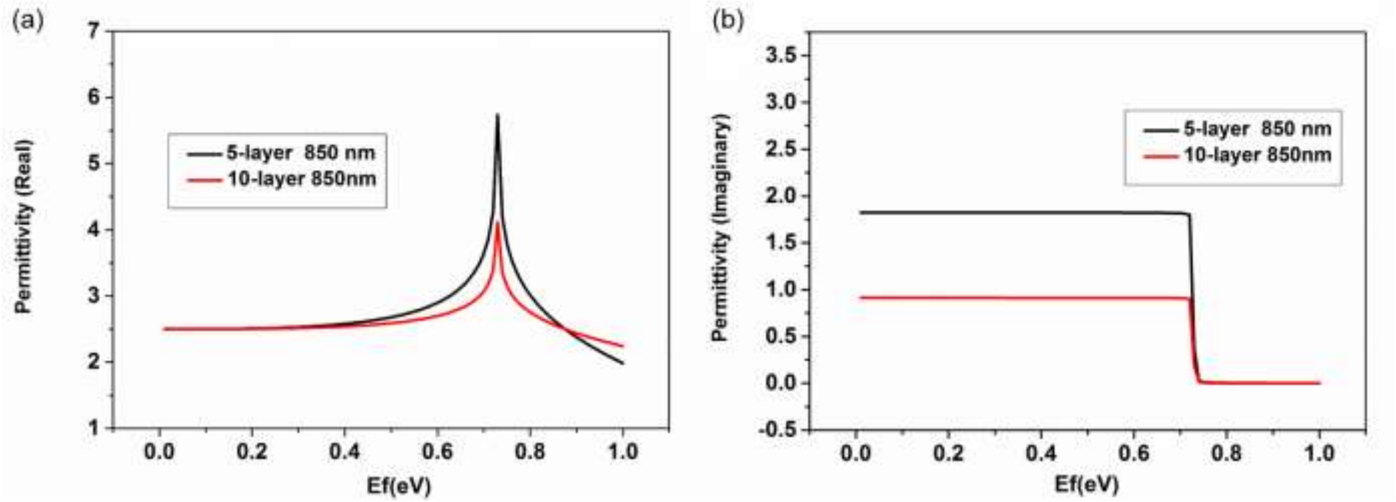

Figure 1. Permittivity of 5-layer and 10-layer graphene under light of 1550 nm and 850 nm. (a) Real permittivity of 5-layer and 10-layer graphene (b) Imaginary permittivity of 5-layer and 10-layer graphene.

B. *Simulation of graphene Fresnel zone plate*

The Fresnel zone plate (FZP) lens is designed to work under 850nm wavelength light, with the radius of the central ring R_1 to be 10μm. The focal length and the radii of the n^{th} rings of a FZP lens satisfy the equation[10]: $\frac{f}{R_n} = \frac{R_n}{n\lambda}$ (λ is the wavelength of light, n = 1, 2, 3…) . So when the incident light is 850 nm, the theoretical focal length should be 117.65 μm. As $n_{max}=23$ in our simulation, the diameter of the lens is about 94 μm.

Due to the radial symmetry of the Fresnel zone plates, 2D simulation was performed, with light coming from y direction and graphene on x direction. Figure 2[11] (a) shows the computed power flow distribution of light reflected by 5-layer graphene FZP, with graphene Fermi level 0.73eV and incident light 850nm. Very clear focal point with high contrast can be seen, which confirms the focusing effect of the reflected light of the graphene-based FZP. The red lines in Figure 2(b) and (c) represent for the horizontal and vertical cross sectional lines at the focal point in Figure 2 (a). The focal distance in the simulation is 114.5nm, which is very close to the theoretical value. The green lines and blue lines are intensity distribution of cross section lines at focal point when the Fermi level of graphene is 0.1 eV and 0.9 eV, respectively. From Figures 2(b) and (c), we can find that the focal intensity of graphene FZP with 0.73eV is almost twice higher than that with Fermi level 0.1eV and 8 times higher than that with Fermi level 0.9 eV. This can be explained by the properties of graphene permittivity, as shown in Figure 1, which illustrates that graphene has different permittivity at different Fermi levels. The focal intensity of graphene FZP with 0.73 eV is much higher than the other two Fermi levels due to the high real permittivity (peak) and low imaginary permittivity(almost 0). The results show that the focal intensity of graphene FZP can be adjusted by changing Fermi levels, which will affect graphene's optical properties, such as dielectric constant and absorption.

Figures 2(d) and (e) demonstrate the influence of the layers of graphene on lensing effect. The focal intensity of graphene FZP is almost doubled when the layer number increases from 5 to 10. This phenomenon is mainly caused by the reflection and absorption will increase along with the increases of graphene layers.

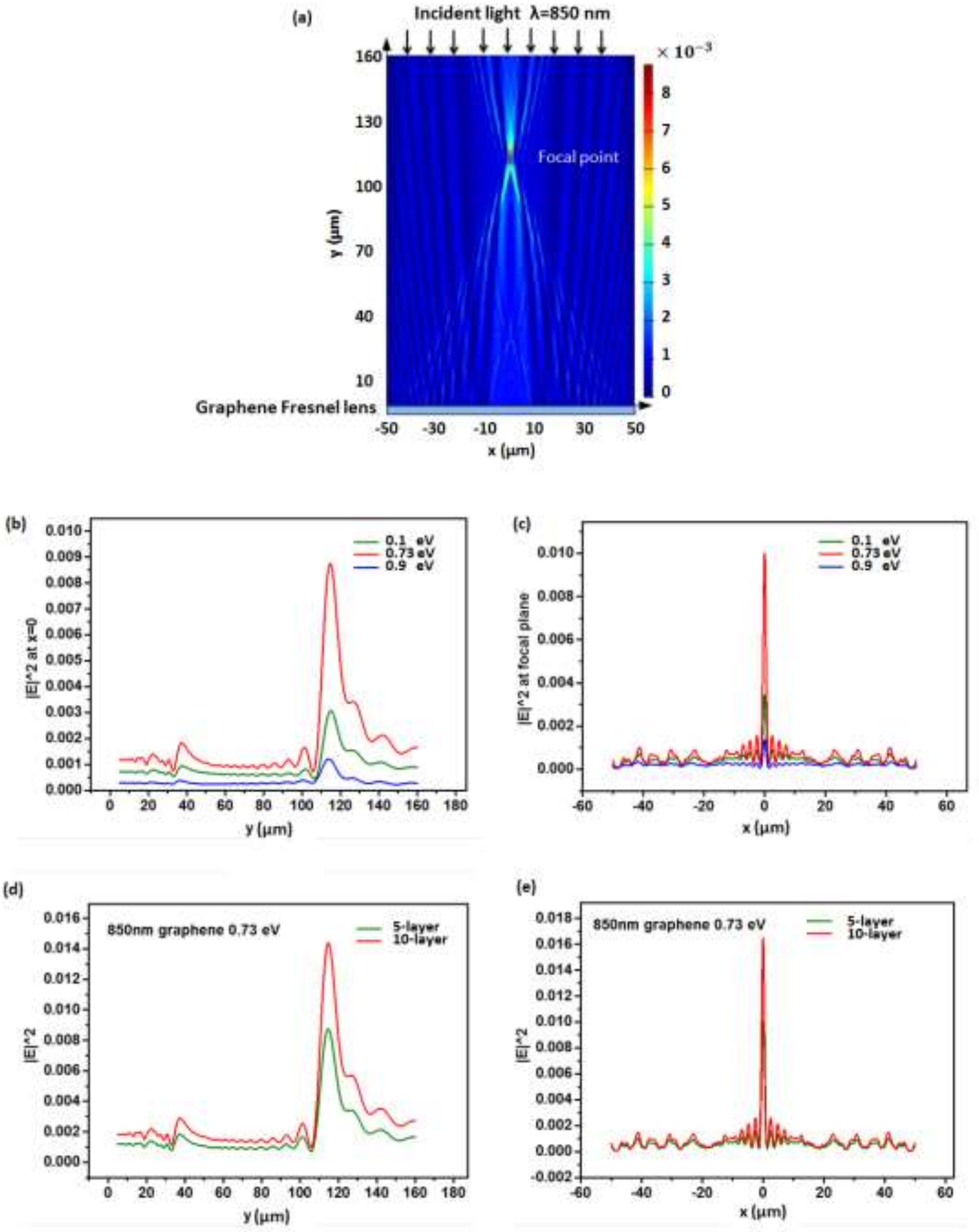

Figure 2[11]. Graphene Fresnel zone plate(FZP) illuminated by light of 850 nm (a) Power flow distribution of light reflected from the 5-layer graphene FZP when illuminated by 850 nm light (Fermi level 0.73 eV). The lens is located at y=0. (b) Power flow distribution across the y-axis, extracted at x=0. (c) Power flow distribution across the x-axis, at the focal plane. In (b) and (c), the green, red and blue lines correspond with graphene Fermi levels of 0.1 eV, 0.73 eV and 0.9 eV respectively. Power flow distribution across (d) y-axis and (e) x-axis for 5-layer (green line) and 10-layer (red line) graphene FZP.

III. Fabrication and characterization of graphene FZP

Multi-layer graphene was synthesized by chemical vapour deposition method[12, 13]. Based on the simulation results, graphene FZPs were fabricated by photolithography methods. The graphene FZPs array are characterized under Alicona microscope, as shown in Figure 3.

Figure 3(a) shows graphene FZPs array on glass substrate. The darker area is graphene while the brighter area is glass with graphene etched away. The FZPs array could focus light with high contrast, as illustrated in Figure 3(b), in which a clear focal point in the middle is visible. Figures (c) and (d) demonstrate the magnified version of a single graphene FZP works as a lens. The experimental focal length of graphene Fresnel lens is 175um±10um, with visible incident light.

According to the FZP work principle, we derive that the incident light wavelength ranges from 540.5nm to 606 nm, which are in the visible regime. Hence, experimental data correspond well with the theoretical value.

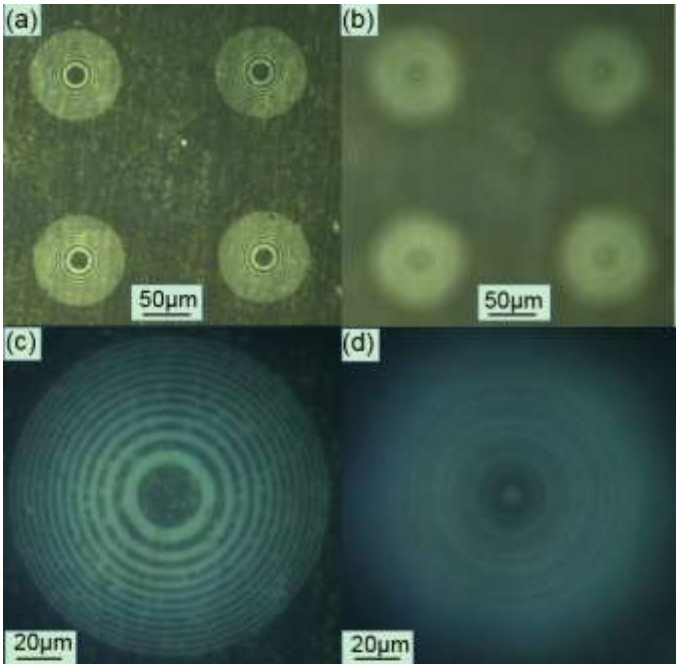

Figure 3. Graphene FZPs under optical microscope. (a) Graphene FZPs lens array (b) focusing light with high contrast. (c) A single graphene lenslet (d) focusing light with good performance

IV. Conclusions

In this paper, we studied the tuneable focusing effect of graphene FZP, which shows that the focusing intensity can be adjusted by changing the Fermi level of graphene under incident light of 850nm wavelength. Then graphene FZPs array were fabricated by lithography technology. Under optical microscope, these graphene FZPs shows high contrast of lensing effect. Our works demonstrate that graphene has the potential to make tuneable ultra-thin flat lens, which are vital in compact systems.

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Our research explores the potential of making ultra-thin and tuneable lenses with graphene, which might bring a radical change to the future of compact optical systems, such as laser focusing for optical storage and fibre-optic communications.