An Accurate Design of Graphene Oxide Ultrathin Flat Lens Based on Rayleigh-Sommerfeld Theory

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**Methods**

**GO film fabrication.** The GO solution are synthesized by a modified Hummer Methods[1]. Then the thickness controllable GO films can be fabricated by filtration method through controlling the mass of GO.

**Femtosecond laser fabrication.** The system sketch is shown in Fig. S1 of the supplement. A low repetition rate, femtosecond pulsed laser beam (100fs pulse, 10 kHz, 800 nm) is used to reduce the GO film through direct laser writing method. By a computer-controlled 3D nanometric piezo stage, 3D arbitrary structures can be created in the sample.

**GO lens characterization**. The system is shown in Fig. S2 of the supplement. The homemade GO lens characterization system has a 633 nm plane wave source, the cross-sectional distributions of the focal spots of the GO lenses are captured with a NA=0.8 objective into a charge-coupled device (CCD) camera. By scanning along the optical axis, we are able to reconstruct the 3D images of the focal spots.

**Supplementary Section 1**

**Lens design method**

The field distribution in the focal region of the ultrathin lens can be calculated using the Rayleigh-Sommerfeld (RS) diffraction theory2:

(1)

where , ***n*** denotes the unit vector normal toward the observe plane, ***r*** is the unit vector of *r* direction from *r*1 to *r*2 as shown in Fig. 1(a). Therefore, we can obtain the field distribution in the focal region in cylindrical coordinate system:

(2)

To design the GO lens with the targeted focal length *f* and diameter D, we only consider the intensity distribution on the *z* axis, namely *r*2=0, *z=f*. Therefore, the field distribution along z axis is:

(3)

Now, for the targeted focal length *f*, is decided by only. Based on the Euler’s equation, the field distribution along z axis can be rewritten as:

(4)

Therefore, the intensity distribution on the *z* axis can be simplified to:

(5)

To find out the minimal points on the intensity distribution *I*(*r*1), taking the derivative of equation 5, we can obtain the contribution of *I*(*r*1) on point *f* along *r*1:

(6)

However,

(7)

where .

As we know:

(8)

(9)

where n is integer greater than or equal to 0. There is no analytic expression of equations 8 and 9, therefore there is no analytic expression of indefinite integral equation 7. We have to use Matlab to find out the minimal points. When we use Matlab, we can program from equation 5 directly.

**Supplementary Section 2**



**Figure S1.** Experimental setup of the laser fabrication system. ES: electronic shutter; BES: beam expanding system; BS1 and BS2: beam splitter; LED: light-emitting diode; Sample: GO film; OBJ: objective; CCD1 and CCD2: charge coupled device.

**Supplementary Section 3**



**Figure S2.** Experimental setup of the GO lens characterization.

1. Qiu, Ling, et al. Biomimetic superelastic graphene-based cellular monoliths. *Nature Commun*. 3, 1241 (2012).
2. Gu, M. Advanced Optical Imaging theory (springer, 2000).