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An accurate design of graphene oxide ultrathin flat lens based on Rayleigh-Sommerfeld theory

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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 theory[1]:

$$U_2(r_2,\theta_2,z)=-\frac{\mathrm{i}}{\lambda}\iint U_1'(r_1,\theta_1)\frac{\exp(\mathrm{i}kr)}{r}\cos(\boldsymbol{n},\boldsymbol{r})\mathrm{d}r_1\mathrm{d}\theta_1 \quad , \tag{1}$$

where $r=[z^2+(x_2-x_1)^2+(y_2-y_1)^2]^{1/2}=[z^2+r_1^2+r_2^2-2r_1r_2\cos(\theta_1-\theta_2)]^{1/2}$, $\boldsymbol{n}$ denotes the unit vector normal toward the observe plane, $\boldsymbol{r}$ 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:

$$U_2(r_2,\theta_2,z)=-\frac{\mathrm{i}}{\lambda}\int_0^{2\pi}\int_0^{\infty}U_1'(r_1,\theta_1)\frac{\exp(-\mathrm{i}k\sqrt{z^2+r_1^2+r_2^2-2r_1r_2\cos(\theta_1-\theta_2)})}{z^2+r_1^2+r_2^2-2r_1r_2\cos(\theta_1-\theta_2)}zr_1\mathrm{d}r_1\mathrm{d}\theta_1 \quad . \tag{2}$$

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:

$$U_2(f)=-\frac{\mathrm{i}}{\lambda}\int_0^{2\pi}\int_0^{\infty}U_1'(r_1,\theta_1)\frac{\exp(-\mathrm{i}k\sqrt{f^2+r_1^2})}{f^2+r_1^2}zr_1\mathrm{d}r_1\mathrm{d}\theta_1=-\frac{\mathrm{i}2\pi}{\lambda}\int_0^{\infty}U_1'(r_1)\frac{\exp(-\mathrm{i}k\sqrt{f^2+r_1^2})}{f^2+r_1^2}fr_1\mathrm{d}r_1 \quad . \tag{3}$$

Now, for the targeted focal length f, $U_2(f)$is decided by r_1 only. Based on the Euler's equation, the field distribution along z axis can be rewritten as:

$$U_2(r_1)=\frac{-2\pi z}{\lambda}\left[\mathrm{i}\int_0^{\infty}U_1(r_1)\frac{\cos(-k\sqrt{z^2+r_1^2})}{z^2+r_1^2}r_1dr_1-\int_0^{\infty}U_1(r_1)\frac{\sin(-k\sqrt{z^2+r_1^2})}{z^2+r_1^2}r_1\mathrm{d}r_1\right] \quad . \tag{4}$$

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

$$I(r_1)=abs\left([(r_1)]^2\right)=\left(\frac{2\pi f}{\lambda}\right)^2\left[\left(\int_0^{\infty}U_1(r_1)\frac{\cos(-k\sqrt{f^2+r_1^2})}{f^2+r_1^2}r_1\mathrm{d}r_1\right)^2+\left(\int_0^{\infty}U_1(r_1)\frac{\sin(-k\sqrt{f^2+r_1^2})}{f^2+r_1^2}r_1\mathrm{d}r_1\right)^2\right] \quad . \tag{5}$$

To find out the maximal destructive interference positions 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:

$$\frac{\mathrm{d}I}{\mathrm{d}r_1}=2\times\left(\frac{2\pi f}{\lambda}\right)^2\left[\left(\frac{\cos(-k\sqrt{f^2+r_1^2})}{f^2+r_1^2}r_1\int_0^{\infty}\frac{\cos(-k\sqrt{f^2+r_1^2})}{f^2+r_1^2}r_1\mathrm{d}r_1\right)+\left(\frac{\sin(-k\sqrt{f^2+r_1^2})}{f^2+r_1^2}r_1\int_0^{\infty}\frac{\sin(-k\sqrt{f^2+r_1^2})}{f^2+r_1^2}r_1\mathrm{d}r_1\right)\right] \quad . \tag{6}$$

However,

$$\int_0^{\infty}\frac{\cos(-k\sqrt{f^2+r_1^2})}{f^2+r_1^2}r_1\mathrm{d}r_1=\int_0^{\infty}\frac{\cos(-k\sqrt{f^2+r_1^2})}{f^2+r_1^2}\frac{1}{2}\mathrm{d}(r_1^2+f^2)=\int_0^{\infty}\frac{1}{2}\frac{\cos(-kR)}{R^2}\mathrm{d}R^2=\int_0^{\infty}\frac{\cos(-kR)}{R}\mathrm{d}R \quad . \tag{7}$$

where $R=(f^2+r_1^2)^{1/2}$.

As we know:

$$\cos R=1-\frac{R^2}{2!}+\frac{R^4}{4!}+(-1)^n\frac{R^{2n}}{(2n)!} \quad , \tag{8}$$

$$\sin R=R-\frac{R^3}{3!}+\frac{R^5}{5!}+(-1)^n\frac{R^{2n+1}}{(2n+1)!} \quad , \tag{9}$$

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 maximal destructive interference positions. When we use Matlab, we can program from equation (5) directly.

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Section 2: Experimental setup of the laser fabrication system

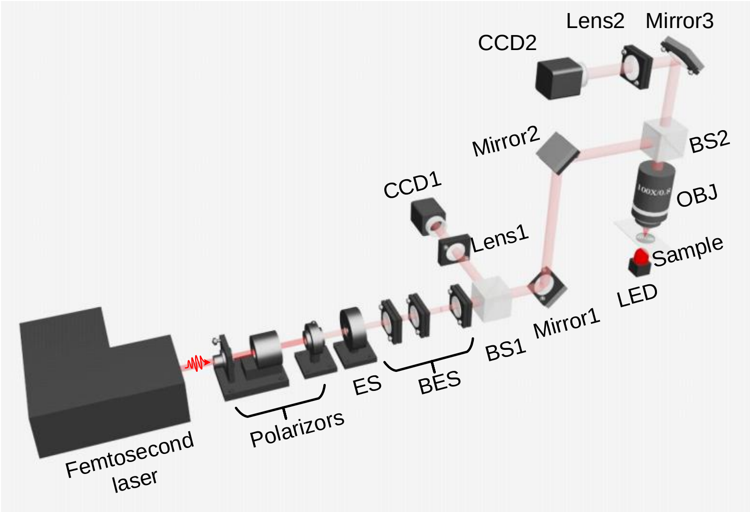

Fig. S1 | Experimental setup of the laser fabrication system. ES: electronic shutter; BES: beam expanding system; BS1 and BS2: beam splitter; LED: light-emitting diode; Sample: GO film; OBJ: objective; CCD1 and CCD2: charge coupled device

Section 3: Experimental setup of the GO lens characterization

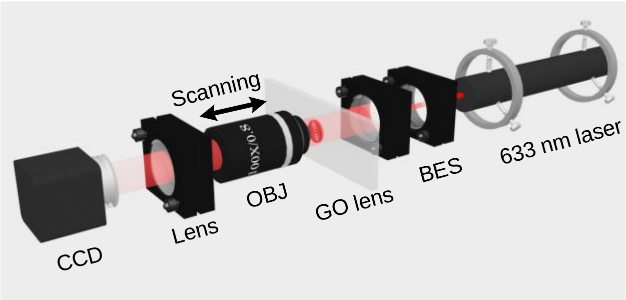

Fig. S2 | Experimental setup of the GO lens characterization.

Supplementary information references

1. Gu M. *Advanced Optical Imaging Theory* (Springer, 2000).