Achievement of Longitudinally Polarized Long Focal Depth Using amplitude filtering

Jie Lin,# Ke Yin and Yuda Li

Center of Ultra-precision Optoelectronic Instrument, Harbin Institute of Technology, Harbin 150001, China
Corresponding Author / E-mail: linjie@hit.edu.cn, TEL: +86-451-86412896-806, FAX: +86-451-86412698

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A longitudinally polarized long focal depth is obtained by using amplitude filtering based on Euler transformation and a radially polarized Bessel–Gaussian beam. In the proposed scheme, the longitudinal component of a focused beam is split into two parts along the optical axis to elongate the depth of focus. Numerical calculation results indicate that depth of focus and full-width at half-maximum (FWHM) can be easily realized with 9.5λ and 0.8λ, respectively. A radially polarized beam can be converted into a longitudinally polarized beam with a conversion efficiency of 51.0%. In experiment, the amplitude filtering can be easily achieved by using of spatial light modulator (SLM). Therefore, it is expected that the proposed scheme can be widely used to generate a longitudinally polarized beam with long focal depth for particle acceleration and optical manipulation.

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1. Introduction

Optical elements with a long focal depth have attracted much interesting in recent years because of their potential application in optical trapping and optical read [1]. Much work has been done on the generation of a line-like focusing along their optical axis of axicon and their derivatives. Phase filtering and polarization of beams were used to achieve focusing with a long focal depth [1,2]. Here, by combining amplitude modulation and a radially polarized Bessel-Gaussian (BG) beam, the Debye integral of the radially polarized BG beam and Euler transformation are implemented to extend the depth of focus (DOF). To validate the proposed method, DOF is obtained with 9λ.

2. Amplitude Filter and Euler Transformation

2.1 Design of Amplitude Filter

As shown in Fig. 1, the radially polarized Bessel-Gaussian beam is focused by a high numerical aperture lens. A filter is introduced to extend the depth of focus. The focused field near the focus z=0 can be solved by Debye integral. The radial component $E_r(r,z)$ and longitudinal component $E_z(r,z)$ can be expressed as following:

$$E_r(r,z) = A\int_0^{\alpha}\cos^{1/2}\theta\sin(2\theta)l(\theta)J_1(kr\sin\theta)e^{ikz\cos\theta}\mathrm{d}\theta, \quad \text{(1)} \quad \text{and} \quad E_z(r,z) = 2iA\int_0^{\alpha}\cos^{1/2}\theta\sin^2\theta l(\theta)J_0(kr\sin\theta)e^{ikz\cos\theta}\mathrm{d}\theta, \quad \text{(2)}$$

where $\alpha = \arcsin(NA/n)$, NA is the numerical aperture of a lens, n is the refractive index. In our scheme, NA and n are 0.95 and 1, respectively. $J_1(x)$ and $J_0(x)$ are first ordered and zero ordered Bessel function. $l(\theta)$ is the amplitude distribution of the incident beam, that is

$$l(\theta) = \exp\left[-\left(\frac{\beta\sin\theta}{\sin\alpha}\right)^2\right]J\left(\frac{2\gamma\sin\theta}{\sin\alpha}\right) \quad \text{(3)}$$

where β and γ are parameters taking as unity. Here we introduce a amplitude filtering function,

$$TR_N(\theta) = \sum_{p=1}^{N}\cos[2M\pi(2p-1)\cos\theta], \quad \text{(4)} \quad \text{and} \quad TR_N(\theta) \text{ is normalized as } T_N(\theta) = TR_N(\theta)/\max[TR_N(\theta)]. \quad \text{(5)}$$

Since $T_N(\theta)$ is introduced into the focus lens and function $l(\theta)$ will be replaced by $l(\theta)T_N(\theta)$. For N=1, considering the Euler transformation, one can obtain

$$T_1(\theta) = \cos(\phi) = 0.5[\exp(i\phi) + \exp(-i\phi)] \quad \text{(6)}$$

where $\phi = kM2\pi\cos\theta$ and therefore, the radial component of electric fields can be given as

$$E_r(r,z) = 0.5A\int_0^{\alpha}\cos^{1/2}\theta\sin(2\theta)l(\theta)J_1(kr\sin\theta)(e^{ik(z-M)\cos\theta} + e^{ik(z+M)\cos\theta})\mathrm{d}\theta \quad \text{(7)}$$

Obviously, Eq. (7) can is equivalent with

$$E_r(r,z)=E_r(r,z-M)+E_r(z+M). \quad \textbf{(8)}$$

From **Eq. *(8)***, focusing at z is split into to two parts at z-M and z+M. It means that the new focusing field has two focuses that it is determined by $\boldsymbol{E_r(r,z\text{-}M)}$ and $\boldsymbol{E_r(z+M)}$, respectively. Obviously, the depth of focus is elongated by the designed amplitude filter with expression **Eq. (5)**. Once parameter M and N is chosen properly, the intensity distribution between two centers is homogeneous and DOF is increased.

2.2 numerical result and analysis

The DOF is 0.8λ only for ***NA***=0.95 without filtering function $T_1(\theta)$. In order to validate the proposed amplitude filtering function, the filtering function with N=1, M=0.9 is applied to the focusing system, and the distance between the two peaks is 1.8λ. The amplitude transmission of the filtering function and the corresponding electric field distributions in the *y*–*z* plane are as shown in Figs. 2(a) and 2(b), respectively. Obviously, Points *A* and *B* represent the peaks located at z-M and z+M, respectively. Thus, a new intensity distribution along optics axis is formed considering the superposition of field distribution with center at Peaks A and B. The DOF is 2.2λ and is lager than that of lens without the filter function, with a FWHM of 0.48λ. Therefore, the validity of the proposed amplitude filtering function is confirmed. Meanwhile, calculated results, as shown in Tab 1, of different parameters (M, N) are explored and compared with the existing works [1]. Scheme *A*, *B*, *C*, *D*, and *E* represent systems without filtering function, with amplitude filtering function with (N=2, M=0.7), with binary optical filtering function in Ref [1], with amplitude filtering function with (N=3, M=0.7), and with amplitude filtering function with (N=4, M=0.7), respectively. Polarization conversion efficiency η is defined as $\eta = \phi_z/(\phi_r+\phi_z)$, where $\phi_{r(z)} = 2\pi\int_0^\infty |E_{r(z)}(r,0)|^2 r\mathrm{d}r$. From Table 1, one can see that the DOF increases with the increase of N. Obviously, DOF with 9.5λ is obtained 9:5λ is twice as large as the previous result [1]. As shown in Fig. 3, If $N\rightarrow\infty$, Eq. (4) is inverted into a two dimensional delta function, i.e., the filtering can be considered as a ring-like function. Previous research results have been indicated that no-diffractive Bessel beam can be generated by combing a ring and lens.

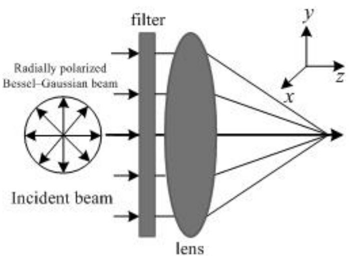

Fig. 1. Schematic of setup with radially polarized BG beam, filter, and high-NA lens.

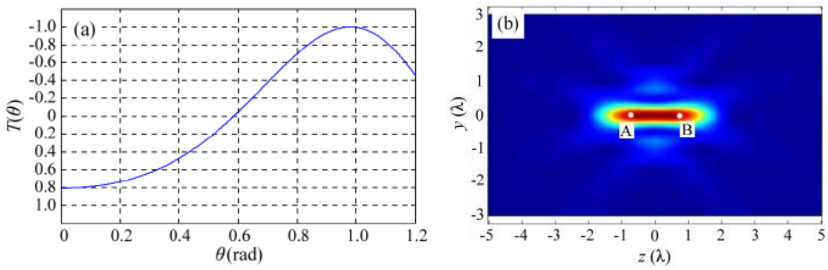

Fig. 2. (a) Amplitude transmittance for N=1, M=0.9, (b) corresponding intensity distribution in the *y*–*z* plane. The DOF obtained is 2.2λ. Points *A* and *B* are the centers of individual focusing with predicted focus points at z-M and z+M.

Table 1. Comparison of Amplitude Filtering Function with Other Filtering

Filtering[a]	DOF (λ)	Conversion efficiency η (%)	HWFM (λ)
A	0.8	44.82	0.68
B	3.8	50.02	0.84
C	4.2	76.52	0.43
D	6.6	51.45	0.74
E	9.5	50.63	0.80

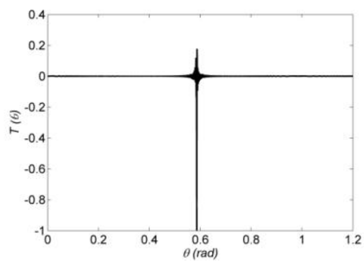

Fig. 3 amplitude transmittance for N=10000, M=0.6.

3. Conclusions

Here an amplitude filter based on Euler transformation and a polarized BG beam is reported to implement longitudinal polarized long focal depth. Numerical results indicate that the scheme can easily achieve long focal depth with DOF 9.5λ and FWHM with 0.8λ and the conversion efficiency is 51.0%. Other numerical results also indicate that long focal depth can be easily obtained using longitudinal splitting.

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