Reply to "Comment on 'Focusing of high polarization order axially-symmetric polarized beams'" [Chin. Opt. Lett. 8, 1110 (2010)]

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This is a reply to the recent comment by Lifeng Li on the paper "Focusing of high polarization order axially-symmetric polarized beams [Chin. Opt. Lett. **7,** 938 (2009)]". We analyze the errors pointed out by the comment, further perfect the mathematical expressions, and present a numerical simulation at last.

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Recently, a comment by Lifeng Li on the paper "Focusing of high polarization order axially-symmetric polarized beams [Chin. Opt. Lett. **7,** 938 (2009)]" is claimed, where some mathematical and conceptual errors are pointed out. Indeed, as proposed in the comment, the mathematical expressions given in Eq. (1) in the Letter "Focusing of high polarization order axially-symmetric polarized beams" for focused fields miss one term in the radial component and another in the azimuthal component, which will affect the computation results of the focused field. The sign of the arguments of the exponential functions is negative. In addition, it is also wrong to adopt a uniform apodization function in the numerical simulation because of the polarization singularity on axis. All these errors should be corrected.

Moreover, a more specific expression can be further achieved on the basis of Eq. (3) given in the comment,

$$\mathbf{E}(r_\mathrm{s},\phi_\mathrm{s},z_\mathrm{s}) = \begin{bmatrix} E_r \\ E_\phi \\ E_z \end{bmatrix} = -\mathrm{i}^{(3P+1)}\frac{\pi E_0 f}{\lambda}\int_0^\alpha l_0(\theta)\sqrt{\cos\theta}\sin\theta\exp(\mathrm{i}kz_\mathrm{s}\cos\theta) \tag{1}$$
$$\times\begin{bmatrix} \cos[(P-1)\phi_\mathrm{s}+\phi_0]\{\cos\theta[J_P(kr_\mathrm{s}\sin\theta)-J_{P-2}(kr_\mathrm{s}\sin\theta)]+J_P(kr_\mathrm{s}\sin\theta)+J_{P-2}(kr_\mathrm{s}\sin\theta)\} \\ \sin[(P-1)\phi_\mathrm{s}+\phi_0]\{\cos\theta[J_P(kr_\mathrm{s}\sin\theta)+J_{P-2}(kr_\mathrm{s}\sin\theta)]+J_P(kr_\mathrm{s}\sin\theta)-J_{P-2}(kr_\mathrm{s}\sin\theta)\} \\ 2\mathrm{i}\cos[(P-1)\phi_\mathrm{s}+\phi_0]\sin\theta J_{P-1}(kr_\mathrm{s}\sin\theta) \end{bmatrix}\mathrm{d}\theta,$$

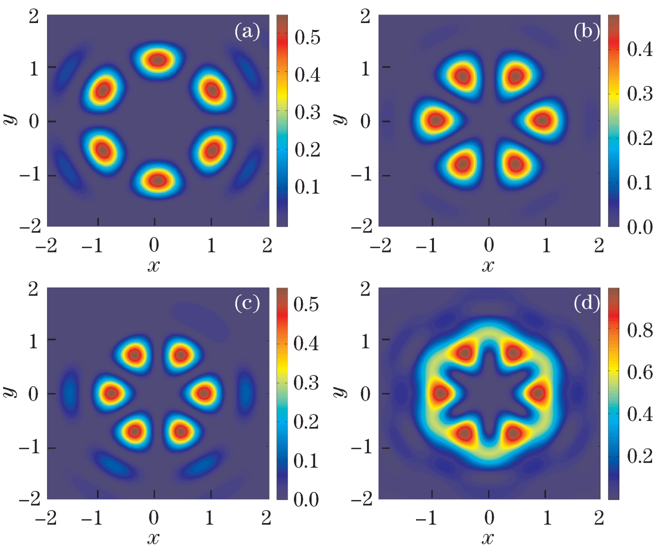

Fig. 1. Intensity distribution of focused field under the condition that P=4, NA=0.90, and ϕ_0=0. (a) $|E_\phi|^2$, (b) $|E_r|^2$, (c) $|E_z|^2$, and (d) total ($|E_\phi|^2+|E_r|^2+|E_z|^2$).

where P is the polarization order of the incident beam, $l_0(\theta)$ is the apodization function, E_0 is the incident field amplitude, and f is the focal length of the lens. The specific expression will enable quantitative estimation in applications such as optical trapping, as well as the rigorous analysis of phase and polarization distribution of focused fields where these details are very important and should be paid attention to.

Figure 1 numerically shows the field intensity $|E|^2$ at focus under the condition that P=4, ϕ_0=0, numerical aperture (NA) is 0.90, and the apodization function

$$l_0(\theta) = \exp\left[-\beta^2\left(\frac{\sin\theta}{\sin\alpha}\right)^2\right]\left(\sqrt{2}\beta\frac{\sin\theta}{\sin\alpha}\right)^P, \tag{2}$$

where $\alpha = \sin^{-1}(\mathrm{NA}/n)$, n is the refractive index. In the simulation, we assume $\beta = 1$, and all length measurements are in units of wavelength.

It is evident that the total focused field presents a multi-focal-spot pattern, and the number of spots is $2\times(P-1)$, which may find wide applications in optical trapping and optical sensing.