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# ELGB在湍流大气中通过圆形光阑的传输特性

费津程，崔执凤，王家驷，屈 军*
（安徽师范大学 物理与电子信息学院，芜湖 241000）

**摘要**：为了研究复宗量拉盖尔-高斯光束在湍流大气中通过圆形光阑的传输特性，采用拓展的惠更斯-菲涅耳原理进行了理论推导和数值计算，得到了光强表达式和相应的计算图像。结果表明，光束在湍流大气中受到光阑限制传输时，当截断参量$\delta<1$，光束能够长距离传输且与源场时的光束横截面光强分布大致类似，仍为空心光束，但中心处光强的归一化值大于0；当截断参量$\delta\geqslant1$时，小孔的衍射效应不明显，与无小孔限制时非常类似，光束横截面光强分布变为高斯形状；大气湍流强度越小，越容易保持源场时的光束横截面光强分布；不同阶数光束在湍流大气中的传输特性也做了相应研究。该结果对于从事激光传输与自由空间光通讯是有帮助的。

**关键词**：大气与海洋光学；复宗量拉盖尔-高斯光束；拓展的惠更斯-菲涅耳原理；湍流大气；光阑
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# Propagation characteristics of elegant Laguerre-Gaussian beam passing through a circular aperture in turbulent atmosphere

*FEI Jin-cheng, CUI Zhi-feng, WANG Jia-si, QU Jun*
(College of Physics and Electronic Information, Anhui Normal University, Wuhu 241000, China)

**Abstract**: In order to study propagation characteristics of elegant Laguerre-Gaussian beam (ELGB) passing through a circular aperture in turbulent atmosphere, corresponding analytical formulate based on the extend Huygens-Fresnel integral were deduced and numerical simulation results were obtained. The results indicate that when the value of the truncation parameter $\delta<1$, the beam profile of ELGB after propagating long distance is similar to that of the source, i. e., hallow beam, but the central normalized intensity is larger than 0; however, the profile tends to Gaussian distribution as the parameter $\delta\geqslant1$. Meanwhile, the weaker the turbulent atmosphere is, the more easily it can preserve the average intensity profile as the source. And the average intensity profiles of different beam orders were also studied. The results are useful to laser beam propagation and free-space laser communication.

**Key words**: atmospheric and ocean optics; elegant Laguerre-Gaussian beam; extend Huygens-Fresnel integral; turbulent atmosphere; aperture

## 引 言

激光光束在自由空间、介质或者大气中传输特性一直受到许多学者的高度关注[1-6]。众所皆知，当光束通过湍流大气时，其相位和振幅要产生一种随机变化，从而导致强度发生波动。近年来，各种激光光束在湍流大气中的传输越来越引起人们的兴趣[7-24]，通常这些研究局限在无光阑限制的情况下。最近，受光阑限制的光束在湍流大气中的传输性质受到人们的注意，并逐渐进行了研究。CHU等人研究了在湍流大气中圆形平顶高斯光束通过圆形光阑时的光强变化情况，研究表明，当截断参量不小于2时，孔径对光束的传输影响可以忽略，当截断参量小于2时，光强轮廓变得非常复杂[25]。GAO等人研究了复宗量拉盖尔-高斯光束(elegant Laguerre-Gaussian beam, ELGB)通过矩形光阑的传输特性，当源平面置于硬边光阑薄透镜后，得到了截断参量越小，光阑的衍射效应越明显，相对焦移随着截断参量的增加而逐渐减小的结论[26]。QING等人研究了拉盖尔-高斯光束通过硬边光阑光学系统的传输，并分析论证了其解析表达式的使用范围同截断参量的关系[27]。SHEN等人研究了在湍流大气中平顶高斯光束通过椭圆形光阑传输时光强和偏振度的分布变化情况[28]。

作者在Rytov近似处理湍流的前提下，以拓展的

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作者简介：费津程(1984-)，男，硕士研究生，主要从事光束传输的研究。
*通讯联系人。E-mail: qujun70@mail.ahnu.edu.cn

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惠更斯-菲涅耳原理[29]为理论基础,利用拉盖尔-高斯光束和厄米-高斯光束之间的变换公式,并通过将光阑函数展开为有限项复高斯函数之和的形式[30],得到了ELGB在湍流大气中通过圆形光阑的光强解析式,同时进行了相应的数值计算。

## 1 理论模型

在傍轴近似条件下,ELGB在源平面($z=0$)的电场表达式为[31]:

$$E_1(r,\theta,0)=\left(\frac{r}{w_0}\right)^m \mathrm{L}_n^m\left(\frac{r^2}{w_0{}^2}\right)\exp\left(-\frac{r^2}{w_0{}^2}\right)\exp(\mathrm{i}m\theta) \tag{1}$$

(1)式建立在柱坐标中,$r$ 和 $\theta$ 分别代表极径和极角。$w_0$ 代表基模高斯光束的束腰宽度,$\mathrm{L}_n{}^m(r^2/w_0{}^2)$ 代表自变量为 $r^2/w_0{}^2$ 的拉盖尔多项式,$m$ 和 $n$ 为变量。令 $\rho=r/w_0$,利用变换公式[32]:

$$\mathrm{e}^{\mathrm{i}m\theta}\rho^m \mathrm{L}_n^m(\rho^2)=\frac{(-1)^n}{2^{2n+m}n!}\times$$

$$\sum_{t=0}^{n}\sum_{s=0}^{m}\mathrm{i}^s\begin{bmatrix}n\\t\end{bmatrix}\begin{bmatrix}m\\s\end{bmatrix}\mathrm{H}_{2t+m-s}(x)\mathrm{H}_{2n-2t+s}(y) \tag{2}$$

式中,$t$ 和 $s$ 为系数,$x$ 和 $y$ 为变量。H为厄米多项式。将(2)式代入(1)式得到在直角坐标系下源场中ELGB的电场表达形式:

$$E_1(x_1,y_1,0)=\frac{(-1)^n}{2^{2n+m}n!}\sum_{t_1=0}^{n}\sum_{s_1=0}^{m}\mathrm{i}^{s_1}\begin{bmatrix}n\\t_1\end{bmatrix}\begin{bmatrix}m\\s_1\end{bmatrix}\times$$

$$\mathrm{H}_{2t_1+m-s_1}\left(\frac{x_1}{w_0}\right)\mathrm{H}_{2n-2t_1+s_1}\left(\frac{y_1}{w_0}\right)\exp\left(-\frac{x_1{}^2}{w_0{}^2}-\frac{y_1{}^2}{w_0{}^2}\right) \tag{3}$$

式中,$x_1$ 和 $y_1$ 分别表示源平面上某一点的横坐标和纵坐标,$\mathrm{H}_{2t_1+m-s_1}\left(\frac{y_1}{w_0}\right)$ 和 $\mathrm{H}_{2n-2t_1+s_1}\left(\frac{y_1}{w_0}\right)$ 表示厄米多项式。当 $m=n=0$ 时,上式退化为基模高斯光束。

现在考虑湍流大气中加上圆形光阑的情况。对于圆形光阑,它的光阑函数可以表示为[28]:

$$f(x,y)=\begin{cases}1,((x-x_0)^2+(y-y_0)^2\leqslant r^2)\\0,(\text{其它})\end{cases} \tag{4}$$

式中,$r$ 代表圆形光阑的半径,$x_0$ 和 $y_0$ 分别代表圆形光阑中心的横坐标和纵坐标。

此时,源平面出发的光束通过圆形光阑时的场强表达式为:

$$E(x_1,y_1,0)=f(x_1,y_1)E_1(x_1,y_1,0) \tag{5}$$

将光阑函数展开为有限项复高斯函数形式[28]:

$$f(x_1,y_1)=\sum_{l=1}^{10}F_l\exp\left\{-\frac{G_l[(x_1-x_0)^2+(y_1-y_0)^2]}{r^2}\right\} \tag{6}$$

式中,$F$ 和 $G$ 为复高斯函数的系数,$l$ 代表复高斯函数展开后的项数。激光从源平面出发,在湍流大气中传输时,根据拓展的惠更斯-菲涅耳原理[29]:

$$E(\rho,z,T)=-\frac{\mathrm{i}k}{2\pi z}\exp(-\mathrm{i}kz)\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}E(r_1,0)\times$$

$$\exp\left[-\frac{\mathrm{i}k}{2z}(r_1-\rho)^2+\Psi(r_1,\rho)-\mathrm{i}2\pi ft\right]\mathrm{d}r_1 \tag{7}$$

式中,$E(r_1,0)$ 和 $E(\rho,z,T)$ 分别是源平面和接收面的电场分布,$z$ 是传输距离,$\Psi(r_1,\rho)$ 描述光从源平面传输到接收面过程中湍流大气引起的随机相位,$T$ 是光束传输时间,$f$ 为光束的频率,$k=2\pi/\lambda$ 为波数。因此,接收面的平均光强为:

$$\langle I(\rho,z)\rangle=\langle E(\rho,z,T)\cdot E^*(\rho,z,T)\rangle=$$

$$\frac{k^2}{4\pi^2z^2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}E(r_1,0)E^*(r_2,0)\times$$

$$\exp\left[-\frac{\mathrm{i}k}{2z}(r_1-\rho)^2+\frac{\mathrm{i}k}{2z}(r_2-\rho)^2\right]\times$$

$$\exp\langle\Psi(r_1,\rho)+\Psi^*(r_2,\rho)\rangle\mathrm{d}r_1\mathrm{d}r_2 \tag{8}$$

式中,$*$ 表示复共轭,$\langle\cdot\rangle$ 表示对湍流介质的系综平均。采用Rytov近似[33]:

$$\langle\exp[\varphi(r_1,p)+\varphi^*(r_2,p)]\rangle_m=$$

$$\exp\left[-\frac{1}{\rho_0{}^2}(x_1-x_2)^2\right]\exp\left[-\frac{1}{\rho_0{}^2}(y_1-y_2)^2\right] \tag{9}$$

式中,$\varphi$ 为相位,$p$ 为接收场点的位置参量。$\rho_0=(0.545C_n{}^2k^2z)^{-3/5}$,$C_n{}^2$ 称为大气折射率常数,表征大气折射率起伏所决定的湍流强弱。

将(3)式,(5)式,(6)式和(9)式代入到(8)式中,得到:

$$I(x,y,z)=\frac{k^2}{4\pi^2z^2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}E(x_1',y_1',0)E^*(x_2',y_2',0)\exp\left\{\frac{\mathrm{i}k}{2z}[(x-x_1')^2-(x-x_2')]\right\}\times$$

$$\exp\left\{\frac{\mathrm{i}k}{2z}[(y-y_1')^2-(y-y_2')^2]\right\}\exp\left[-\frac{1}{\rho_0{}^2}(x_1'-x_2')^2\right]\exp\left[-\frac{1}{\rho_0{}^2}(y_1'-y_2')^2\right]\mathrm{d}x_1'\mathrm{d}x_2'\mathrm{d}y_1'\mathrm{d}y_2'=$$

$$\frac{k^2}{4\pi^2z^2}\sum_{l=1}^{10}\sum_{z=1}^{10}\sum_{t_1=0}^{n}\sum_{s_1=0}^{m}\sum_{t_2=0}^{n}\sum_{s_2=0}^{m}\mathrm{i}^{s_1}(-\mathrm{i})^{s_2}\frac{1}{2^{4n+2m}(n!)^2}\begin{bmatrix}n\\t_1\end{bmatrix}\begin{bmatrix}m\\s_1\end{bmatrix}\begin{bmatrix}n\\t_2\end{bmatrix}\begin{bmatrix}m\\s_2\end{bmatrix}\times$$

$$\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}F_l\exp\left\{-\frac{G_l[(x_1'-x_0)^2+(y_1'-y_0)^2]}{r^2}\right\}\mathrm{H}_{2t_1+m-s_1}\left(\frac{x_1'}{w_0}\right)\mathrm{H}_{2n-2t_1+s_1}\left(\frac{y_1'}{w_0}\right)\exp\left(-\frac{x_1'^2}{w_0{}^2}-\frac{y_1'^2}{w_0{}^2}\right)\times$$

$$F_z^*\exp\left\{-\frac{G_z^*[(x_2'-x_0)^2+(y_2'-y_0)^2]}{r^2}\right\}\mathrm{H}_{2t_2+m-s_2}\left(\frac{x_2'}{w_0}\right)\mathrm{H}_{2n-2t_2+s_2}\left(\frac{y_2'}{w_0}\right)\exp\left(-\frac{x_2'^2}{w_0^2}-\frac{y_2'^2}{w_0^2}\right)\times$$
$$\exp\left\{\frac{ik}{2z}[(x-x_1')^2-(x-x_2')^2]\right\}\exp\left\{\frac{ik}{2z}[(y-y_1')^2-(y-y_2')^2]\right\}\times$$
$$\exp\left[-\frac{1}{\rho_0^2}(x_1'-x_2')^2\right]\exp\left[-\frac{1}{\rho_0^2}(y_1'-y_2')^2\right]\mathrm{d}x_1'\mathrm{d}x_2'\mathrm{d}y_1'\mathrm{d}y_2' \tag{10}$$

为方便计算，圆形光阑的中心坐标选在原点，即 $x_0=y_0=0$，利用积分公式[34]：

$$\int_{-\infty}^{\infty}x^n\exp(-px^2+2qx)\mathrm{d}x=n!\sqrt{\frac{\pi}{p}}\left(\frac{q}{p}\right)^n\exp\left[\frac{q^2}{p}\right]\times\sum_{k=0}^{n/2}\frac{1}{(n-2k)!k!}\left(\frac{p}{4q^2}\right)^k\int_{-\infty}^{\infty}\exp[-(x-y)^2]\times\mathrm{H}_n(\alpha x)\mathrm{d}x=\sqrt{\pi}(1-\alpha^2)^{n/2}\mathrm{H}_n\left[\frac{\alpha y}{(1-\alpha^2)^{1/2}}\right] \tag{11}$$

式中，$q$ 为接收场点的位置参量。(11)式和重要关系式 $\mathrm{H}_n(z)=\sum_{k=0}^{n/2}\frac{(-1)^k n!}{k!\,(n-2k)!}(2z)^{n-2k}$，$(a+b)^n=\sum_{k}^{n}\begin{bmatrix}n\\k\end{bmatrix}a^k b^{n-k}$，经过一系列复杂的数学运算可得下式，即为本文中得到的主要表达式：

$$I(x,y,z)=\frac{k^2}{4\pi^2z^2}\frac{1^2}{2^{4n+2m}(n!)^2}\mathrm{i}^{s_1}(-\mathrm{i})^{s_2}(-1)^{u_1+u_2+v_1+v_2}\times$$
$$\sum_{l=1}^{10}\sum_{z=1}^{10}\sum_{t_1=0}^{n}\sum_{s_1=0}^{m}\sum_{t_2=0}^{n}\sum_{s_2=0}^{m}\sum_{u_1=0}^{\frac{2t_1+m-s_1}{2}}\sum_{u_2=0}^{\frac{2n-2t_1+s_1}{2}}\sum_{v_1=0}^{\frac{2t_2+m-s_2}{2}}\sum_{v_2=0}^{\frac{2n-2t_2+s_2}{2}}\sum_{k_1=0}^{2t_1+m-s_1-2u_1}\sum_{k_2=0}^{2n-2t_1+s_1-2u_2}\sum_{j_1=0}^{\frac{2t_2+2m-s_2-2v_1+2t_1-s_1-2u_1-k_1}{2}}\sum_{j_2=0}^{\frac{2n-2t_2+s_2-2v_2+2n-2t_1+s_1-2u_2-k_2}{2}}\begin{bmatrix}n\\t_1\end{bmatrix}\times$$
$$\begin{bmatrix}m\\s_1\end{bmatrix}\begin{bmatrix}n\\t_2\end{bmatrix}\begin{bmatrix}m\\s_2\end{bmatrix}\begin{bmatrix}2t_1+m-s_1-2u_1\\k_1\end{bmatrix}\begin{bmatrix}2n-2t_1+s_1-2u_2\\k_2\end{bmatrix}\times$$
$$F_lF_z^*\frac{(2t_1+m-s_1)!}{u_1!(2t_1+m-s_1-2u_1)!}\frac{(2n-2t_1+s_1)!}{u_2!(2n-2t_1+s_1-2u_2)}\frac{(2t_2+m-s_2)!}{v_1!(2t_2+m-s_2-2v_1)!}\frac{(2n-2t_2+s_2)!}{v_2!(2n-2t_2+s_2-2v_2)}\times$$
$$\frac{(2t_2+2m-s_2-2v_1+2t_1-s_1-2u_1-k_1)!}{(2t_2+2m-s_2-2v_1+2t_1-s_1-2u_1-k_1-2j_1)!j_1!}\times\frac{(2n-2t_2+s_2-2v_2+2n-2t_1+s_1-2u_2-k_2)!}{(2n-2t_2+s_2-2v_2+2n-2t_1+s_1-2u_2-k_2-2j_2)!j_2!}\times$$
$$2^{2m-2v_1+4n-2v_2-2j_1-2j_2-2u_1-2u_2}\frac{\pi^2}{P_1P_2}\left(1-\frac{1}{w_0^2P_1}\right)^{\frac{m+2n}{2}}\left(\frac{1}{w_0}\right)^{2n+m-2v_1-2v_2}\times\left[\frac{A_1}{w_0P_1\left(1-\frac{1}{w_0^2P_1}\right)^{\frac{1}{2}}}\right]^{k_1+k_2}\left[\frac{B_1}{w_0P_1\left(1-\frac{1}{w_0^2P_1}\right)^{\frac{1}{2}}}\right]^{2n+m-2u_1-2u_2-k_1-k_2}\times$$
$$\left(\frac{Q_1}{P_2}\right)^{4n+2m-2v_1-2v_2-2u_1-2u_2-k_1-k_2}x^{2t_2+2m-s_2-2v_1+2t_1-s_1-2u_1-2j_1}y^{4n-2t_2+s_2-2v_2-2t_1+s_1-2u_2-2j_2}\times$$
$$\left(\frac{P_2}{Q_1^2}\right)^{j_1+j_2}\exp\left[\frac{A_1^2(x^2+y^2)}{P_1}+\frac{Q_1^2(x^2+y^2)}{P_2}\right] \tag{12}$$

式中，$A_1=-\frac{ik}{2z}$，$B_1=\frac{1}{\rho_0^2}$，$P_1=\frac{G_l}{r^2}+\frac{1}{w_0^2}+A_1+B_1$，$P_2=\frac{G_z^*}{r^2}+\frac{1}{w_0^2}-A_1+B_1-\frac{B_1^2}{P_1}$，$Q_1=-A_1+\frac{A_1B_1}{P_1}$。对于(12)式，当 $r\to\infty$ 时，即ELGB在湍流大气中传输，没有受到光阑限制；当 $\rho_0\to\infty$ 时，即ELGB在自由空间中传输，受到圆形光阑的限制；当 $r\to\infty$，$\rho_0\to\infty$ 时，即ELGB在自由空间中传输，不受光阑限制。

## 2 数值计算

根据前边得到的解析表达式，选取不同的参量对湍流大气中无光阑以及湍流大气中有光阑的情形进行数值计算。图1a表示在源平面上的光强分布，图1b、图1c和图1d分别表示不同传输距离时，湍流大气无光阑、湍流大气中截断参量 $\delta=0.5$ 和湍流大气中截断参量 $\delta=1$ 的光束横截面光强分布。通过图1可以看出，光束在湍流大气中传输时，当传输距离相对较近时，例如 $z=1\mathrm{km}$ 时，与源场时的光束横截面光强分布相类似，保持空心光束形状，但中心点光强归一化值较源场大。随着传输距离的增加，例如 $z=3\mathrm{km}$ 和 $z=8\mathrm{km}$ 时，光强分布轮廓发生很大变化，呈现高斯形状。当在湍流大气中加上截断参量 $\delta=0.5$ 的光阑时，无论传输距离远近，都与源场光束横截面光强分布类似，保持空心光束形状，但随着传输距离的增加，中心处所对应的光强归一化值变大，在 $z=1\mathrm{km}$ 和 $z=3\mathrm{km}$ 时，由于光阑的衍射效应，出现明显的衍

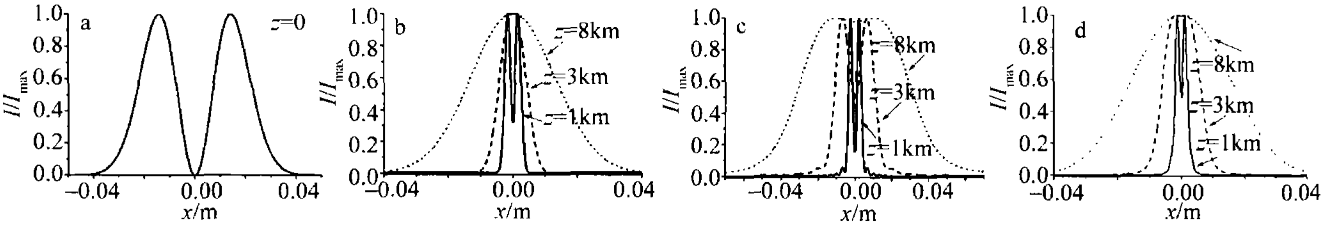

Fig. 1 The average intensity profile at different distances in turbulent atmosphere, the calculation parameters are $m = 1, n = 0, \lambda = 6.328 \times 10^{-7}\mathrm{m}, w_0 = 0.02\mathrm{m}, C_n^2 = 5 \times 10^{-15}\mathrm{m}^{-2/3}$

a—at the source plane b—without aperture c—the parameter $\delta = 0.5$ d—the parameter $\delta = 1$

射旁瓣。在湍流大气中加上截断参量的光阑时，小孔的衍射效应可以忽略不计，所得到的图像与不加小孔限制时非常类似。

图 2 中给出了光束传输一定距离时，不同强度湍流对有光阑和无光阑时光强分布的影响情况。作者发现，$z = 3\mathrm{km}$，湍流大气中无论是否加光阑，当 $C_n^2 = 5 \times 10^{-4}\mathrm{m}^{-2/3}$ 时，其光强形状为高斯形状，见图 2c 和图 2d；当 $C_n^2 = 5 \times 10^{-15}\mathrm{m}^{-2/3}$ 和 $C_n^2 = 5 \times 10^{-16}\mathrm{m}^{-2/3}$ 时，光强形状发生变化。受到光阑限制时，湍流强度越小，保持源场时的光束横截面光强分布的趋势越明显。

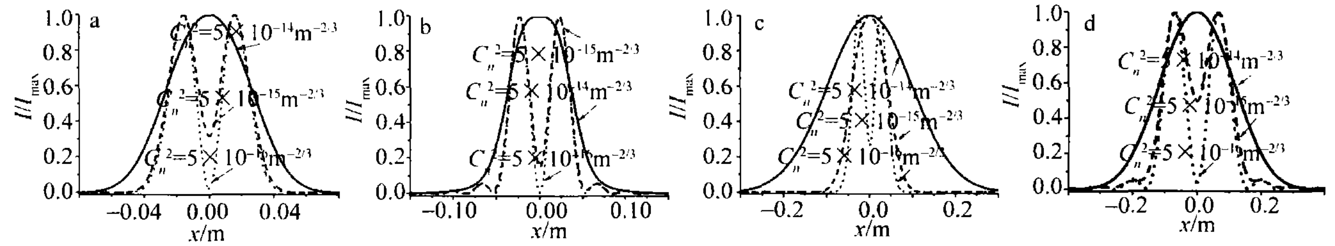

Fig. 2 The average intensity profile at different distances in turbulent atmosphere, the calculation parameters are $m = 1, n = 0, \lambda = 6.328 \times 10^{-7}\mathrm{m}, w_0 = 0.02\mathrm{m}$

a—$z = 1\mathrm{km}$ b—$z = 1\mathrm{km}$ and the parameter $\delta = 0.5$ c—$z = 3\mathrm{km}$ d—$z = 3\mathrm{km}$ and the parameter $\delta = 0.5$

图 3a 和图 3b 分别描述的是当传输距离 $z = 1\mathrm{km}$ 时，在湍流大气中有光阑和无光阑时，不同阶数的光强分布；图 3c 和图 3d 分别描述的是当传输距离 $z = 3\mathrm{km}$ 时，在湍流大气中有光阑和无光阑时，不同阶数的光强分布。由图 3 可以看出，当湍流大气中无光阑时，各个阶数的光束没有重合，而加上截断参量为 $\delta = 0.5$ 的光阑之后，$m = n = 1$ 的光束与 $m = 1, n = 0$ 的光束光强分布重合。这是由于复宗量拉盖尔-高斯光束是空心光束的一种，当 $m = 1, n = 0$ 和 $m = 1, n = 1$，且截断参量为 0.5 时，通过光阑的光束实质是横截面分布相似的光束，因而造成了传输面上光强分布重合的现象。

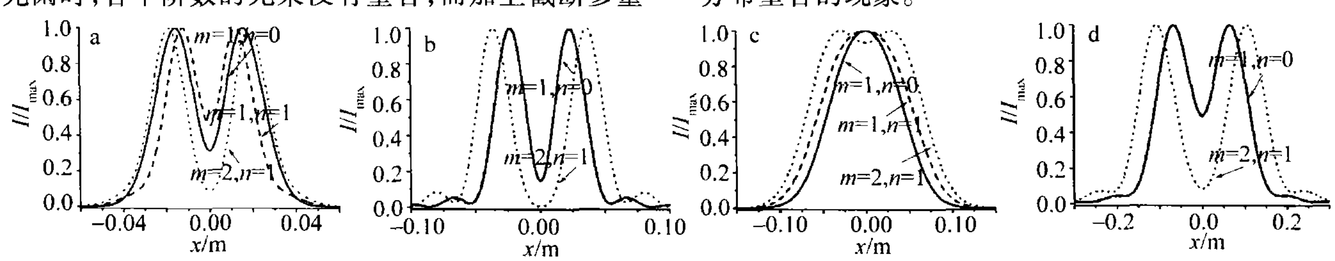

Fig. 3 The average intensity profile at different distances in turbulent atmosphere, the calculation parameters are $C_n^2 = 5 \times 10^{-15}\mathrm{m}^{-2/3}, \lambda = 6.328 \times 10^{-7}\mathrm{m}, w_0 = 0.02\mathrm{m}$

a—$z = 1\mathrm{km}$ b—$z = 1\mathrm{km}$ and the parameter $\delta = 0.5$ c—$z = 3\mathrm{km}$ d—$z = 3\mathrm{km}$ and the parameter $\delta = 0.5$

## 3 结 论

从拓展的惠更斯-菲涅耳原理出发，通过将光阑函数展开为有限项复高斯函数之和的方法，推导得到了 ELGB 在湍流大气中通过圆形光阑的光强公式，并数值计算了截断参量对光束传输过程中光强分布的影响，所得结论对实际光束传输与通讯有一定的参考价值。

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