补充材料

柱矢量涡旋光束在自由空间中传输时角动量的全矢量特性*

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APVB 的理论模型及分析

1 理论模型

当 RPVB 在自由空间中传输时，设定 $z = 0$ 处为光束的源平面，RPVB 在源平面处电场表示为

$$
\begin{aligned}
\boldsymbol{E}(x_0, y_0, 0) = {} & [x_0 + \mathrm{i}\,\mathrm{sgn}(m)\,y_0]^{|m|} \exp\left(-\frac{x_0^2 + y_0^2}{w_0^2}\right) \\
& \times \left(\frac{x_0}{w_0}\boldsymbol{e}_x + \frac{y_0}{w_0}\boldsymbol{e}_y\right)\exp[-\mathrm{i}kz]
\end{aligned}
\tag{S1}
$$

式中 x_0 和 y_0 是源平面上的位置矢量，m 代表拓扑荷，w_0 为束腰半径，$\boldsymbol{e}_x$ 和 $\boldsymbol{e}_y$ 是 x 方向和 y 方向上的单位向量．RPVB 在自由空间中传输了距离 z 后的电场如公式(S2a)所示．式中 $w(z)$ 表示光束在 z 处束腰宽度，$R(z)$ 表示波前曲率半径，z_R 表示瑞利距离，k 表示波数，λ 表示波长．本文中 λ 取 632.8 nm，传输距离 $z = 298.785\ \mu m$，需要说明传输距离 z 可以为任意数值，传输方向为-z 方向．

$$
\begin{aligned}
\boldsymbol{E}(x, y, z) = {} & [x + \mathrm{i}\,\mathrm{sgn}(m)\,y]^{|m|} \exp\left[-\left(\frac{x^2 + y^2}{w(z)^2}\right)\right] \\
& \times \exp\left[-\frac{\mathrm{i}k(x^2 + y^2)}{2R(z)}\right]\left(\frac{w_0}{w(z)}\right)\left(\frac{x}{w(z)}\boldsymbol{e}_x + \frac{y}{w(z)}\boldsymbol{e}_y\right)\exp[-\mathrm{i}kz]
\end{aligned}
\tag{S2a}
$$

$$
w(z) = w_0\sqrt{1 + z^2/z_R^2}
\tag{S2b}
$$

$$
R(z) = z\left(1 + z_R^2/z^2\right)
\tag{S2c}
$$

$$
z_R = \pi w_0^2/\lambda
\tag{S2d}
$$

$$
k = 2\pi/\lambda
\tag{S2e}
$$

从上式可以得到RPVB在自由空间中传输了距离z后不同分量的电场表达式如公式(S3a)和(S3b)所示，表示为

$$E_x = \left[x + i\,\mathrm{sgn}(m)y\right]^{|m|} \exp\left[-\left(\frac{x^2 + y^2}{w(z)^2}\right)\right]$$

$$\times \exp\left[-\frac{ik(x^2 + y^2)}{2R(z)}\right]\left(\frac{w_0}{w(z)}\right)\frac{x}{w(z)}\boldsymbol{e}_x \exp\left[-ikz\right] \tag{S3a}$$

$$E_y = \left[x + i\,\mathrm{sgn}(m)y\right]^{|m|} \exp\left[-\left(\frac{x^2 + y^2}{w(z)^2}\right)\right]$$

$$\times \exp\left[-\frac{ik(x^2 + y^2)}{2R(z)}\right]\left(\frac{w_0}{w(z)}\right)\frac{y}{w(z)}\boldsymbol{e}_y \exp\left[-ikz\right] \tag{S3b}$$

其中x和y表示接收平面上的位置矢量. 公式(S4)表示了径向偏振光与角向偏振光之间的偏振关系

$$\left|\begin{matrix} \boldsymbol{E}_x \\ \boldsymbol{E}_y \end{matrix}\right|_{azimuthally} = \left|\begin{matrix} -\boldsymbol{E}_y \\ \boldsymbol{E}_x \end{matrix}\right|_{radially} \tag{S4}$$

因此APVB在自由空间中传输距离z后不同分量的电场表达式如公式(S5a)和(s5b)所示，表示为

$$E_x = -\left[x + i\,\mathrm{sgn}(m)y\right]^{|m|} \exp\left[-\left(\frac{x^2 + y^2}{w(z)^2}\right)\right]$$

$$\times \exp\left[-\frac{ik(x^2 + y^2)}{2R(z)}\right]\left(\frac{w_0}{w(z)}\right)\frac{y}{w(z)}\boldsymbol{e}_y \exp\left[-ikz\right] \tag{S5a}$$

$$E_y = \left[x + i\,\mathrm{sgn}(m)y\right]^{|m|} \exp\left[-\left(\frac{x^2 + y^2}{w(z)^2}\right)\right]$$

$$\times \exp\left[-\frac{ik(x^2 + y^2)}{2R(z)}\right]\left(\frac{w_0}{w(z)}\right)\frac{x}{w(z)}\boldsymbol{e}_x \exp\left[-ikz\right] \tag{S5b}$$

根据傍轴近似中电场和磁场之间的关系，相应的磁场分量可以表示为

$$H_x = \frac{k}{\omega\mu}E_y\boldsymbol{e}_x = \frac{k}{\omega\mu}\left[x + i\,\mathrm{sgn}(m)y\right]^{|m|} \exp\left[-\left(\frac{x^2 + y^2}{w(z)^2}\right)\right]$$

$$\times \exp\left[-\frac{ik(x^2 + y^2)}{2R(z)}\right]\left(\frac{w_0}{w(z)}\right)\frac{x}{w(z)}\boldsymbol{e}_x \exp\left[-ikz\right] \tag{S6a}$$

$$H_y = -\frac{k}{\omega\mu}E_x\boldsymbol{e}_y = \frac{k}{\omega\mu}\left[x + i\,\mathrm{sgn}(m)y\right]^{|m|} \exp\left[-\left(\frac{x^2 + y^2}{w(z)^2}\right)\right]$$

$$\times \exp\left[-\frac{ik(x^2 + y^2)}{2R(z)}\right]\left(\frac{w_0}{w(z)}\right)\frac{y}{w(z)}\boldsymbol{e}_y \exp\left[-ikz\right] \tag{S6b}$$

2 分　析
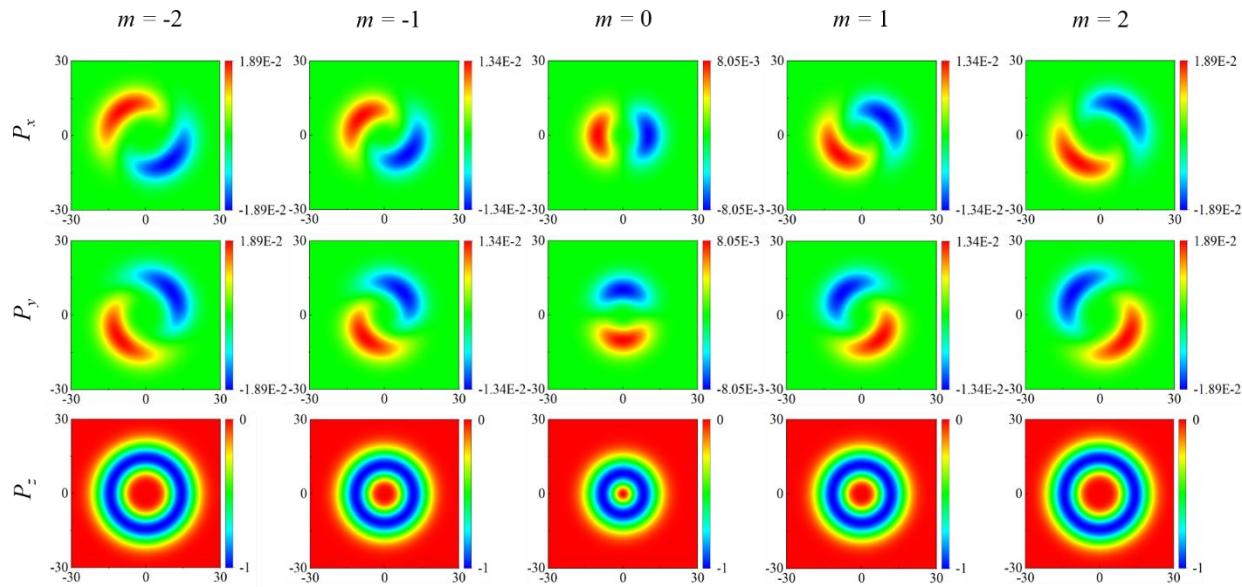
图S1 拓扑荷 $m = 0, \pm1, \pm2$ 时APVB在自由空间距离源平面 z 处动量 (P) 的 x, y, z 分量. 带有不同拓扑荷 m 的APVB的动量分量通过除以相应拓扑荷 m 下总光强的最大值进行归一化

Fig. S1. The x, y, z components of kinetic momentum (P) of APVB in free space from the source plane z when the topological charge $m = 0, \pm1, \pm2$. The momentum components of APVB with different topological charges are normalized by dividing by the maximum value of the total light intensity of the corresponding topological charge m.
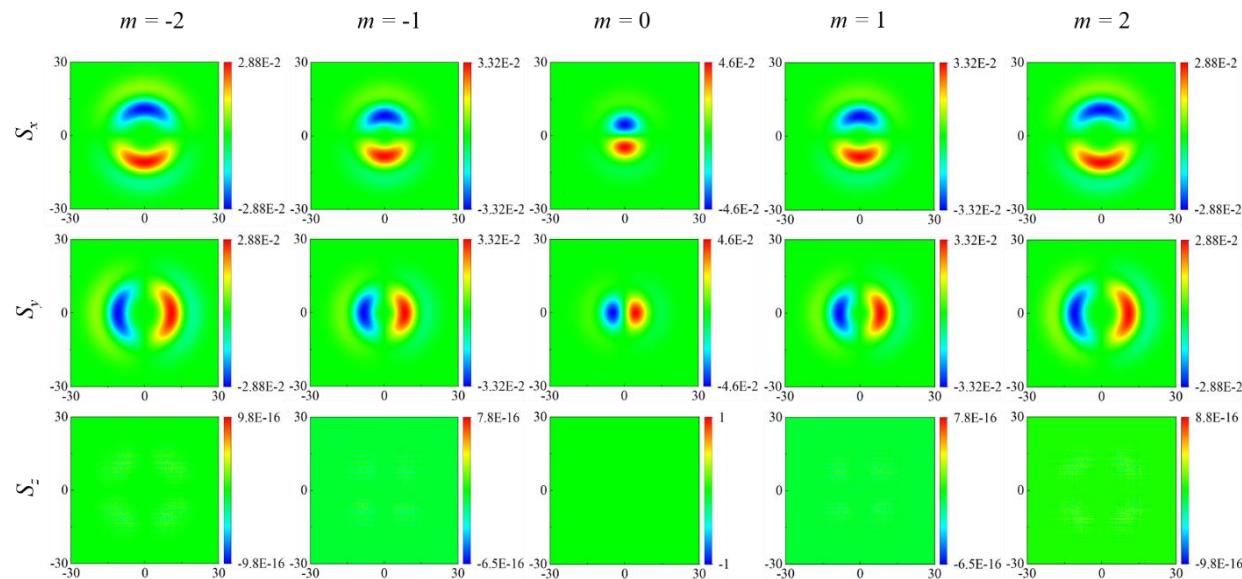
图S2 拓扑荷 $m = 0, \pm1, \pm2$ 时APVB在自由空间距离源平面 z 处总SAM的 x, y, z 分量. 带有不同拓扑荷 m 的APVB的总SAM分量通过除以相应拓扑荷 m 下总光强的最大值进行归一化

Fig. S2. The x, y, z components of the total SAM of APVB in free space from the source plane z when the topological charge $m = 0, \pm1, \pm2$. The total SAM component of APVB with different topological charges is normalized by dividing by the maximum valve of the total light intensity of the corresponding topological charge m.
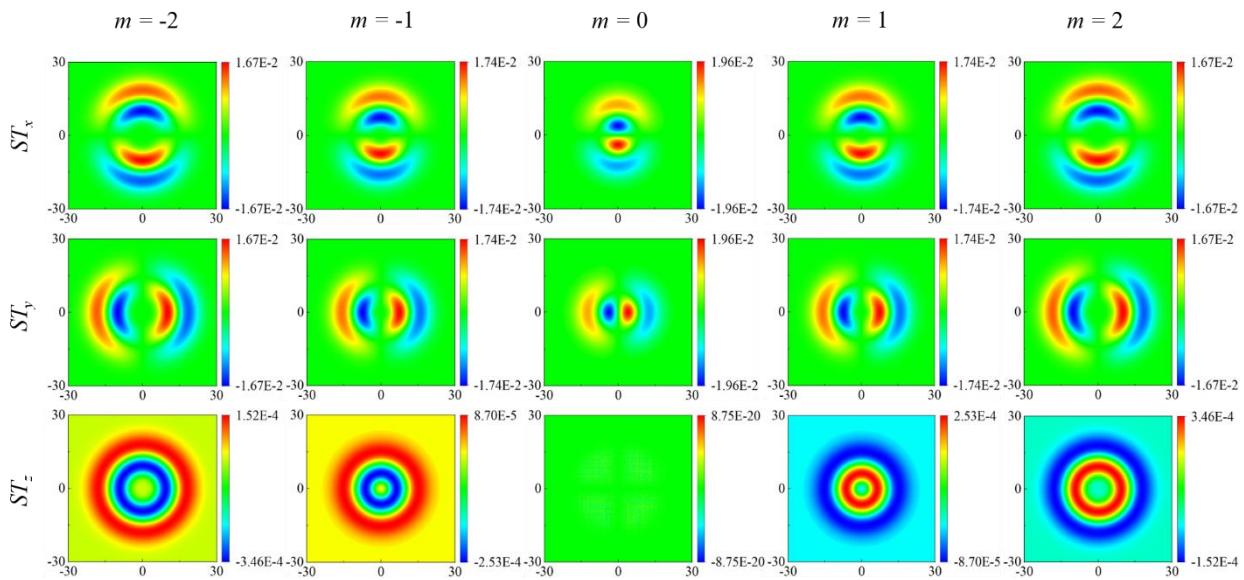
图S3　拓扑荷 $m = 0, \pm1, \pm2$ 时APVB在自由空间距离源平面 z 处横向自旋(t-SAM)的 x, y, z 分量. 带有不同拓扑荷 m 的APVB的 t-SAM的分量通过除以相应拓扑荷 m 下总光强的最大值进行归一化.

Fig. S3.　The x, y, z components of the transverse-type spin (t-SAM) of APVB in free space from the source plane z when the topological charge $m = 0, \pm1, \pm2$. The components of the t-SAM of APVB with different topological charges are normalized by dividing by the maximum value of the total light intensity of the corresponding topological charge m.
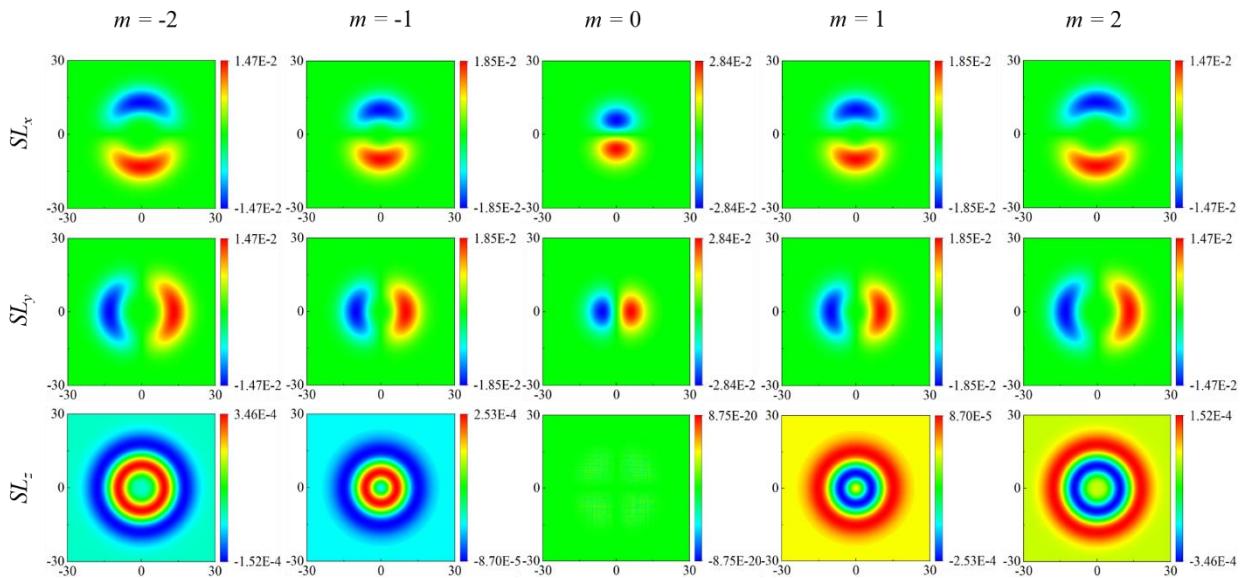

图 S4　拓扑荷 $m = 0, \pm1, \pm2$ 时 APVB 在自由空间距离源平面 z 处纵向自旋(l-SAM)的 x, y, z 分量. 带有不同拓扑荷 m 的 APVB 的 l-SAM 的分量通过除以相应拓扑荷 m 下总光强的最大值进行归一化

Fig. S4.　The x, y, z components of the longitudinal-type spin (l-SAM) of APVB in free space from the source plane z when the topological charge $m = 0, \pm1, \pm2$. The components of the l-SAM of APVB with different topological charges are normalized by dividing by the maximum value of the total light intensity of the corresponding topological charge m.
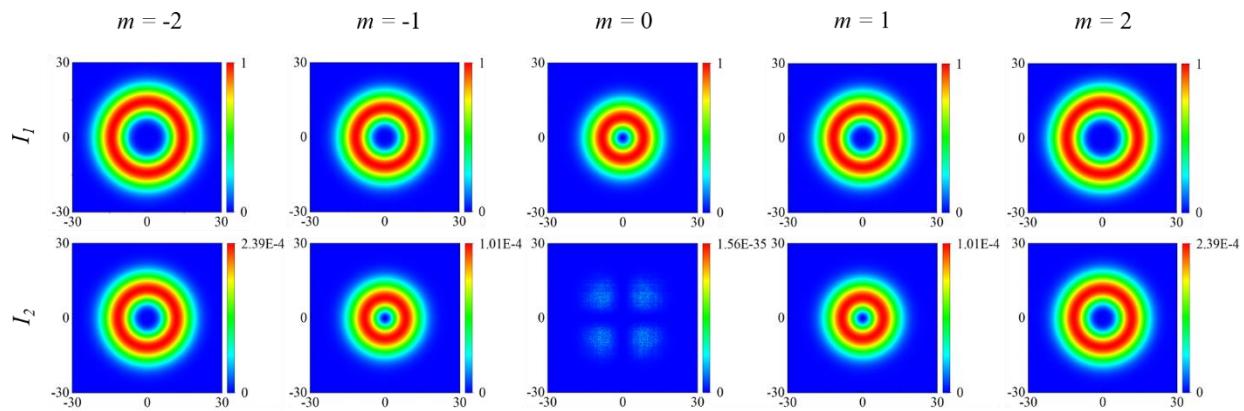
图S5 拓扑荷 $m=0, \pm1, \pm2$ 时APVB在自由空间距离源平面 z 处的横向场和纵向场光强.带有不同拓扑荷 m 的APVB的横向场和纵向场光强通过除以相应拓扑荷 m 下 I_1+I_2 的最大值进行归一化

Fig. S5.　The transverse field and longitudinal field intensity of APVB in free space from the source plane z when the topological charge $m = 0, \pm1, \pm2$. The transverse and longitudinal field light intensities of APVB with different topological charges are normalized by dividing by the maximum value of $I_1 + I_2$ of the corresponding topological charge m.
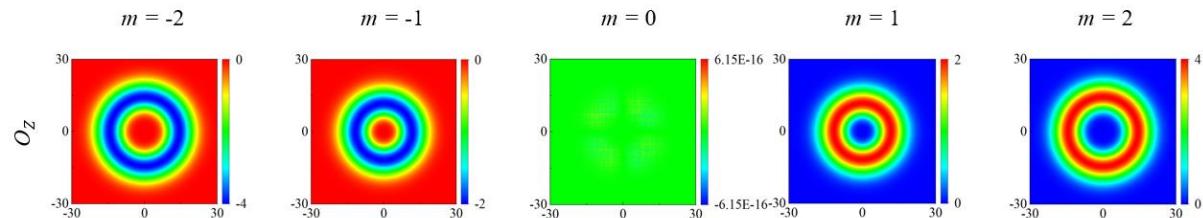

图 S6 拓扑荷 $m = 0, \pm1, \pm2$ 时 APVB 在自由空间距离源平面 z 处的 OAM. 带有不同拓扑荷 m 的 APVB 的 OAM 通过除以相应拓扑荷 m 下 $I_1 + I_2$ 的最大值进行归一化

Fig. S6.　The OAM of APVB in free space from the source plane z when the topological charge $m = 0, \pm1, \pm2$. The OAM of APVB with different topological charges is normalized by dividing by the maximum value of $I_1 + I_2$ of the corresponding topological charge number m.