

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

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

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, \mathbf{e}_x 和 \mathbf{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 $z = 298.785 \mu\text{m}$, 需要说明传输距离 z 可以为任意数值, 传输方向为 $-z$ 方向.

$$\begin{aligned} \mathbf{E}(x, y, z) = & [x + i \operatorname{sgn}(m) y]^{|m|} \exp\left[-\left(\frac{x^2 + y^2}{w(z)^2}\right)\right] \\ & \times \exp\left[-\frac{ik(x^2 + y^2)}{2R(z)}\right] \left(\frac{w_0}{w(z)}\right) \left(\frac{x}{w(z)} \mathbf{e}_x + \frac{y}{w(z)} \mathbf{e}_y\right) \exp[-ikz] \end{aligned} \quad (\text{S2a})$$

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

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

$$z_R = \pi w_0^2 / \lambda \quad (\text{S2d})$$

$$k = 2\pi / \lambda \quad (\text{S2e})$$

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

$$\begin{aligned} \mathbf{E}_x &= [x + i \operatorname{sgn}(m)y]^{|m|} \exp\left[-\left(\frac{x^2 + y^2}{w(z)^2}\right)\right] \\ &\times \exp\left[-\frac{ik(x^2 + y^2)}{2R(z)}\right] \left(\frac{w_0}{w(z)}\right) \frac{x}{w(z)} \mathbf{e}_x \exp[-ikz] \end{aligned} \quad (\text{S3a})$$

$$\begin{aligned} \mathbf{E}_y &= [x + i \operatorname{sgn}(m)y]^{|m|} \exp\left[-\left(\frac{x^2 + y^2}{w(z)^2}\right)\right] \\ &\times \exp\left[-\frac{ik(x^2 + y^2)}{2R(z)}\right] \left(\frac{w_0}{w(z)}\right) \frac{y}{w(z)} \mathbf{e}_y \exp[-ikz] \end{aligned} \quad (\text{S3b})$$

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

$$\begin{bmatrix} \mathbf{E}_x \\ \mathbf{E}_y \end{bmatrix}_{\text{azimuthally}} = \begin{bmatrix} -\mathbf{E}_y \\ \mathbf{E}_x \end{bmatrix}_{\text{radially}} \quad (\text{S4})$$

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

$$\begin{aligned} \mathbf{E}_x &= -[x + i \operatorname{sgn}(m)y]^{|m|} \exp\left[-\left(\frac{x^2 + y^2}{w(z)^2}\right)\right] \\ &\times \exp\left[-\frac{ik(x^2 + y^2)}{2R(z)}\right] \left(\frac{w_0}{w(z)}\right) \frac{y}{w(z)} \mathbf{e}_y \exp[-ikz] \end{aligned} \quad (\text{S5a})$$

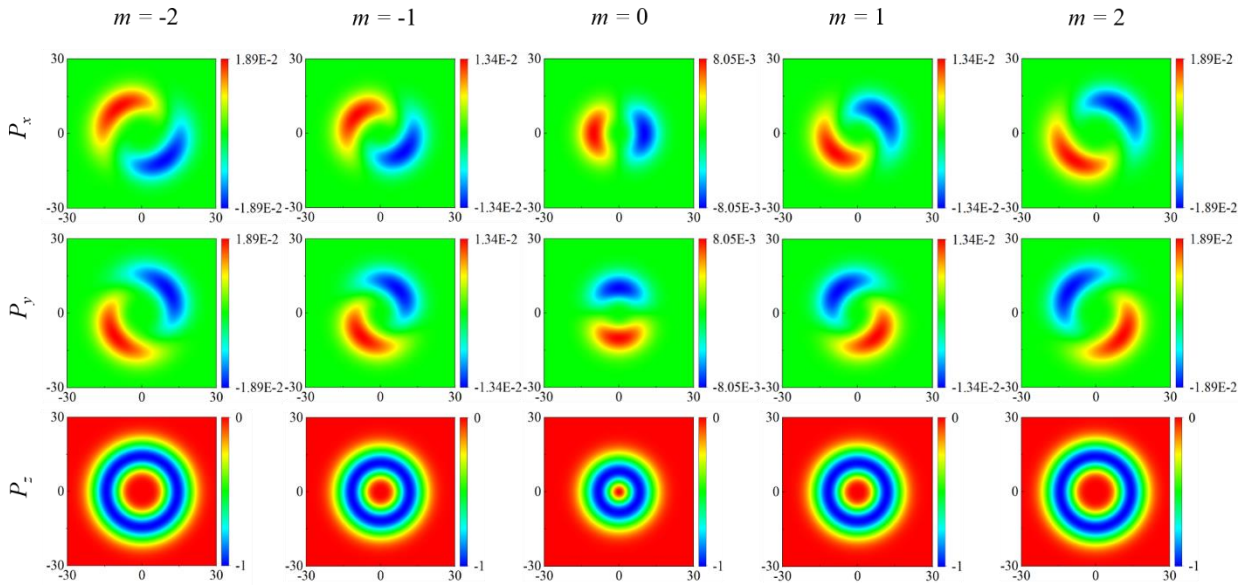
$$\begin{aligned} \mathbf{E}_y &= [x + i \operatorname{sgn}(m)y]^{|m|} \exp\left[-\left(\frac{x^2 + y^2}{w(z)^2}\right)\right] \\ &\times \exp\left[-\frac{ik(x^2 + y^2)}{2R(z)}\right] \left(\frac{w_0}{w(z)}\right) \frac{x}{w(z)} \mathbf{e}_x \exp[-ikz] \end{aligned} \quad (\text{S5b})$$

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

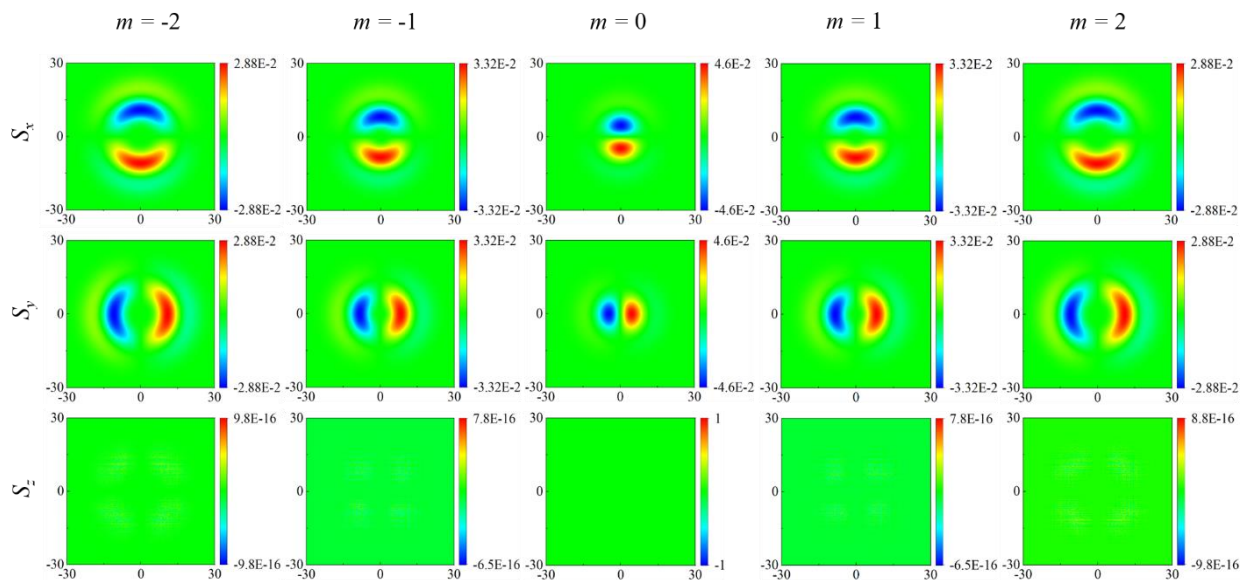
$$\begin{aligned} \mathbf{H}_x &= \frac{k}{\omega\mu} E_y \mathbf{e}_x = \frac{k}{\omega\mu} [x + i \operatorname{sgn}(m)y]^{|m|} \exp\left[-\left(\frac{x^2 + y^2}{w(z)^2}\right)\right] \\ &\times \exp\left[-\frac{ik(x^2 + y^2)}{2R(z)}\right] \left(\frac{w_0}{w(z)}\right) \frac{x}{w(z)} \mathbf{e}_x \exp[-ikz] \end{aligned} \quad (\text{S6a})$$

$$\begin{aligned} \mathbf{H}_y &= -\frac{k}{\omega\mu} E_x \mathbf{e}_y = \frac{k}{\omega\mu} [x + i \operatorname{sgn}(m)y]^{|m|} \exp\left[-\left(\frac{x^2 + y^2}{w(z)^2}\right)\right] \\ &\times \exp\left[-\frac{ik(x^2 + y^2)}{2R(z)}\right] \left(\frac{w_0}{w(z)}\right) \frac{y}{w(z)} \mathbf{e}_y \exp[-ikz] \end{aligned} \quad (\text{S6b})$$

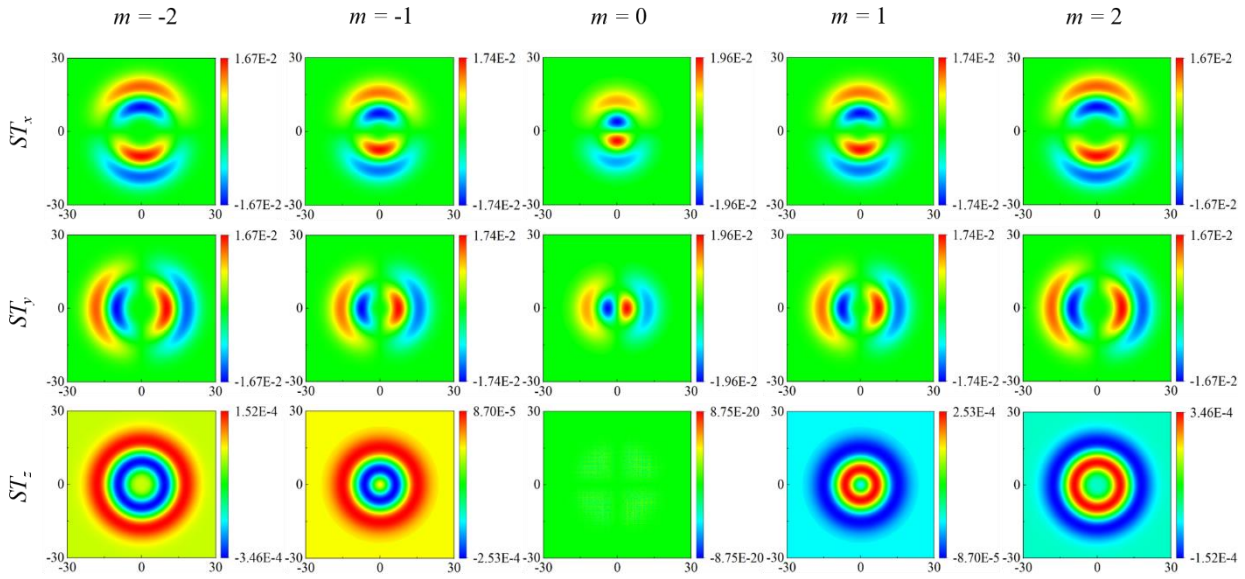
2 分 析



图S1 拓扑荷 $m = 0, \pm 1, \pm 2$ 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 $m = 0, \pm 1, \pm 2$. 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 $m = 0, \pm 1, \pm 2$ 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 $m = 0, \pm 1, \pm 2$. The total SAM component of APVB with different topological charges is normalized by dividing by the maximum value of the total light intensity of the corresponding topological charge m .



图S3 拓扑荷 $m = 0, \pm 1, \pm 2$ 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 $m = 0, \pm 1, \pm 2$. 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 .

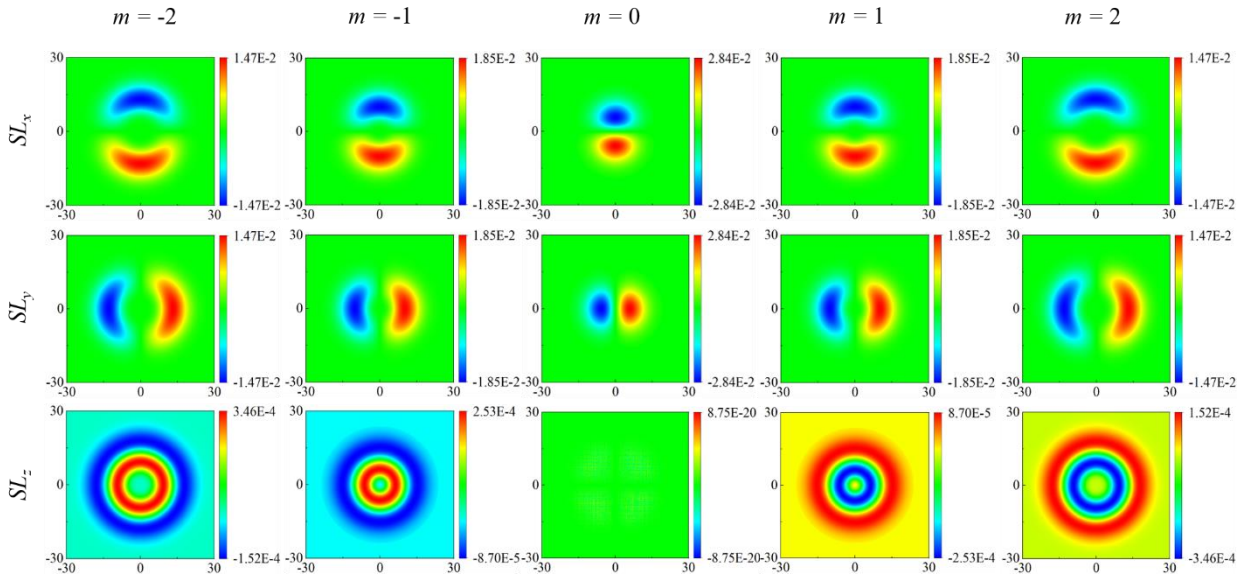
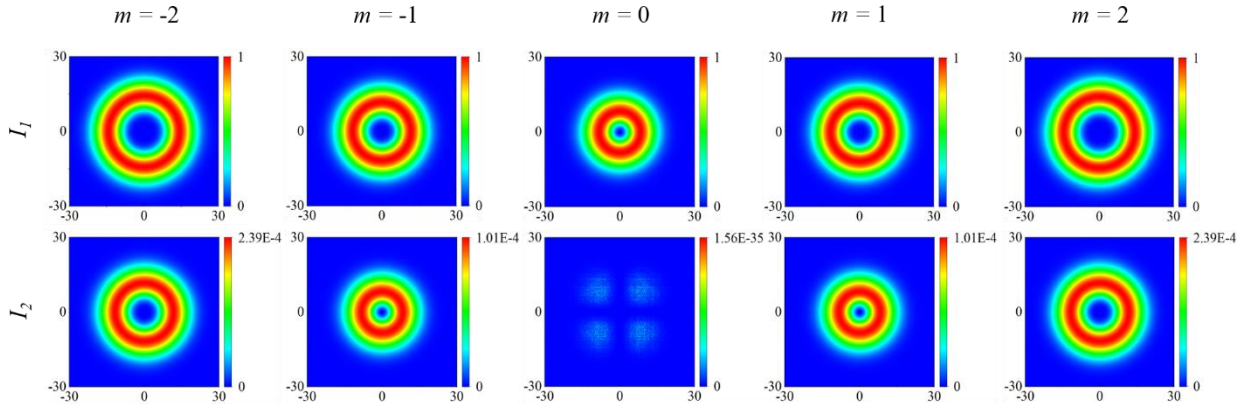


图 S4 拓扑荷 $m = 0, \pm 1, \pm 2$ 时 APVB 在自由空间距离源平面 z 处纵向自旋 (l -SAM) 的 x, y, z 分量. 带有不同拓扑荷 m 的 APVB 的 l -SAM 的分量通过除以相应拓扑荷 m 下总光强的最大值进行归一化

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 $m = 0, \pm 1, \pm 2$. 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 $m=0, \pm 1, \pm 2$ 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 $m = 0, \pm 1, \pm 2$. 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 .

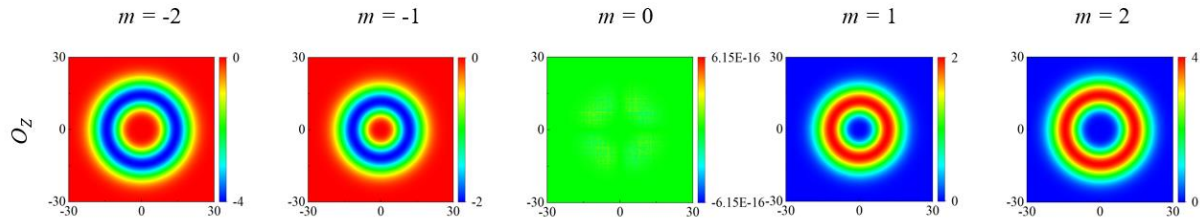


图 S6 拓扑荷 $m = 0, \pm 1, \pm 2$ 时 APVB 在自由空间距离源平面 z 处的 OAM. 带有不同拓扑荷 m 的 APVB 的 OAM 通过除以相应拓扑荷 m 下 $I_1 + I_2$ 的最大值进行归一化

Fig. S6. The OAM of APVB in free space from the source plane z when the topological charge $m = 0, \pm 1, \pm 2$. 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 .