

非线性倒抛物型梯度折射率棒透镜 两正交极化光束的物象变换¹

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摘 要 从标量麦克斯韦方程出发, 对一类克尔非线性倒抛物型梯度折射率棒透镜中两正交极化高斯光束, 用变分法推导出并求解了无量纲束宽参量的非线性耦合微分方程. 研究了棒透镜中两正交极化光束的场和经棒透镜物象变换的性质.

关键词 梯度折射率, 棒透镜, 成象

中图分类号 TN929.1

1 引 言

非线性媒质中光场自聚焦特性的发现和研究的三十多年. 非线性系数达 $10^{-14} \text{ m}^2/\text{W}$ 的掺铒光纤, 也已在光纤放大器和光纤激光器中获得了重要应用^[1,2]. 在许多实际激光系统中, 光场为高斯分布. 由于梯度折射率棒透镜获得了广泛应用^[3], 已有许多文献^[4-7]报道了各类非线性梯度折射率棒透镜内高斯光束的光场以及经棒透镜的物象变换特性. 本文从标量麦克斯韦方程出发, 用变分法^[8,9]分析了两正交极化高斯光束经克尔非线性倒抛物型梯度折射率棒透镜传播的光场分布. 导出并求解了两光束无量纲束宽参量的二阶非线性耦合微分方程. 结合高斯光束传播的 ABCD 定律^[10], 研究了光束参量对光经棒透镜变换的影响, 讨论了一束光对另一束光的光场和物象变换的影响.

2 场的变分解

两正交极化光束的电场

$$\mathbf{E} = E_1 \hat{x} + E_2 \hat{y}, \quad (1)$$

射入折射率分布为

$$n = n_0 + n_2 I, \quad n_0^2 = n_{co}^2 [1 - A(z)r^2], \quad (2)$$

$$A(z) = A_0 / (1 + A_1 z^2)^2, \quad A(z)r^2 \ll 1, \quad A_0 > 0, \quad A_1 > 0 \quad (3)$$

的克尔非线性倒抛物型梯度折射率棒透镜, (1) 式中的 \hat{x} 和 \hat{y} 分别为 x 轴和 y 轴方向的单位矢量, E_1 和 E_2 分别为沿 x 轴和 y 轴方向极化的电场; n_0 为线性时 (零功率) 的倒抛物型梯度折射率分布^[11]; n_2 为非线性系数^[4-7,9]; I 为功率密度^[9]; n_{co} 为棒轴心的折射率; $r = \sqrt{x^2 + y^2}$ 为径向半径; z 为轴向传播距离; A_0 和 A_1 为棒折射率分布的结构参数. 由 (1) 式得棒内功率密度后代入 (2) 式得折射率分布的平方近似:

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$$n^2 = n_0^2 + \alpha(|E_1|^2 + |E_2|^2), \quad \alpha = n_{co}^2 n_2 c \epsilon_0, \quad (4)$$

式中 c 和 ϵ_0 分别为真空中的光速和介电常数。

如图 1 和图 2 所示, 入射的沿 x 轴极化的高斯光束的束腰半径为 ω_{01} , 束腰至棒入射端面 ($z = 0$) 的距离为 L_{01} (物距), 经棒透镜变换后出射光束的束腰半径为 ω_{31} , 束腰至棒出射端面 ($z = Z$) 的距离为 L_1 (象距); 入射的沿 y 轴极化的高斯光束的束腰半径为 ω_{02} , 束腰至棒入射端面的距离为 L_{02} (物距), 经棒透镜变换后出射光束的束腰半径为 ω_{32} , 束腰至棒出射端面的距离为 L_2 (象距). 棒入射端面处两光束的束宽半径分别为^[10]

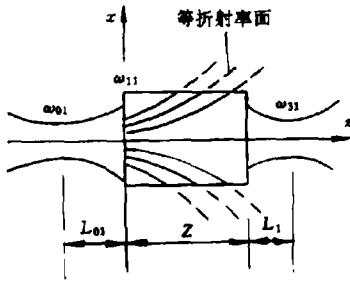


图 1 x 轴方向极化光束经棒透镜的传播和变换

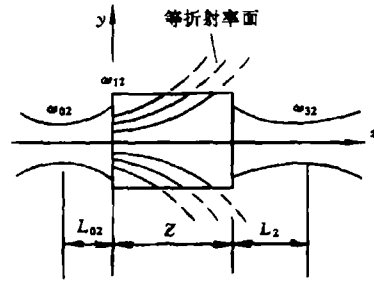


图 2 y 轴方向极化光束经棒透镜的传播和变换

$$\omega_{11} = \omega_{01} \sqrt{1 + (L_{01}/Z_{01})^2}, \quad \omega_{12} = \omega_{02} \sqrt{1 + (L_{02}/Z_{02})^2}, \quad (5)$$

式中 $Z_{01} = \pi\omega_{01}^2/\lambda$, $Z_{02} = \pi\omega_{02}^2/\lambda$, λ 为真空中的光波长. 波前曲率半径的倒数分别为^[10]

$$\rho_{11} = L_{01}/[n_{co}(L_{01}^2 + Z_{01}^2)], \quad \rho_{12} = L_{02}/[n_{co}(L_{02}^2 + Z_{02}^2)]. \quad (6)$$

两光束射入棒后, 电场分别为

$$E_1 = \psi_1(r, z) \exp(-ikz), \quad E_2 = \psi_2(r, z) \exp(-ikz), \quad (7)$$

式中 $k = 2\pi n_{co}/\lambda$. 依标量麦克斯韦方程得

$$\frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial \psi_1}{\partial r} \right) - 2ik \frac{\partial \psi_1}{\partial z} - k^2 A(z) r^2 \psi_1 + \frac{\alpha k^2}{n_{co}^2} (|\psi_1|^2 + |\psi_2|^2) \psi_1 = 0, \quad (8)$$

$$\frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial \psi_2}{\partial r} \right) - 2ik \frac{\partial \psi_2}{\partial z} - k^2 A(z) r^2 \psi_2 + \frac{\alpha k^2}{n_{co}^2} (|\psi_1|^2 + |\psi_2|^2) \psi_2 = 0, \quad (9)$$

上两方程中, 已设 ψ_1 和 ψ_2 为 z 的缓变函数, 略去了 $\partial^2 \psi_1 / \partial z^2$ 和 $\partial^2 \psi_2 / \partial z^2$. (8), (9) 式可表述为变分问题 $\delta \iint J r dr dz = 0$, 式中

$$J = \frac{k\alpha}{4n_{co}^2} (\psi_1 \psi_1^* + \psi_2 \psi_2^*)^2 + \sum_{j=1}^2 \left[\frac{i}{2} (\psi_j \frac{\partial \psi_j^*}{\partial z} - \psi_j^* \frac{\partial \psi_j}{\partial z}) - \frac{1}{2k} \frac{\partial \psi_j}{\partial r} \frac{\partial \psi_j^*}{\partial r} - \frac{1}{2} k A(z) r^2 \psi_j \psi_j^* \right]. \quad (10)$$

设电场的试探解为^[12]

$$\psi_1(r, z) = [\psi_{01}/\omega_1(z)] \exp\{-[r^2/(\omega_{11}^2\omega_1^2(z))] - (ik\rho_1(z)r^2/2) + i\phi_1(z)\}, \quad (11)$$

$$\psi_2(r, z) = [\psi_{02}/\omega_2(z)] \exp\{-[r^2/(\omega_{12}^2\omega_2^2(z))] - (ik\rho_2(z)r^2/2) + i\phi_2(z)\}, \quad (12)$$

式中 ψ_{01} 和 ψ_{02} 分别为两光束的初始幅度; ω_1 和 ω_2 分别为两光束的无量纲束宽参量; ρ_1 和 ρ_2 分别为两光束波前曲率半径的倒数; ϕ_1 和 ϕ_2 分别为两光束的纵向相位. 将上两式代入 (10) 式求积分 $\langle J \rangle = \int J r dr$, 再依简化的 Euler-Lagrange 方程

$$\frac{\partial \langle J \rangle}{\partial y_i} - \frac{d}{dz} \left[\frac{\partial \langle J \rangle}{\partial (dy_i/dz)} \right] = 0, \quad (13)$$

式中 $y_i = \psi_{0j}, \omega_j, \rho_j, \phi_j, j = 1, 2$, 得

$$\frac{d^2\omega_1}{dz^2} + A(z)\omega_1 = \frac{B_1}{\omega_1^3} \left[1 - Q_1 - \frac{4Q_2}{(1 + (\omega_{12}^2\omega_2^2)/(\omega_{11}^2\omega_1^2))^2} \right], \quad (14)$$

$$\frac{d^2\omega_2}{dz^2} + A(z)\omega_2 = \frac{B_2}{\omega_2^3} \left[1 - Q_2 - \frac{4Q_1}{(1 + (\omega_{11}^2\omega_1^2)/(\omega_{12}^2\omega_2^2))^2} \right], \quad (15)$$

$$\rho_1 = (1/\omega_1)(d\omega_1/dz), \quad \rho_2 = (1/\omega_2)(d\omega_2/dz). \quad (16)$$

式中 $Q_1 = P_1/P_c$ 和 $Q_2 = P_2/P_c$ 分别为两光束的归一化功率; $P_c = \lambda^2/(2\pi n_2 n_{co})$ 为临界自聚焦功率; $P_1 = \pi c \epsilon_0 n_{co} \int \psi_1 \psi_1^* r dr$ 和 $P_2 = \pi c \epsilon_0 n_{co} \int \psi_2 \psi_2^* r dr$ 分别为两光束功率; $B_1 = 4/(k^2 \omega_{11}^4)$, $B_2 = 4/(k^2 \omega_{12}^4)$. 此处略去了有关 ϕ_1 和 ϕ_2 的方程. 边界条件为

$$\omega_1(0) = \omega_2(0) = 1, \quad \frac{d\omega_1}{dz} \Big|_{z=0} = \rho_{11}, \quad \frac{d\omega_2}{dz} \Big|_{z=0} = \rho_{12}. \quad (17)$$

变量作如下代换

$$u = \tan^{-1}(\sqrt{A_1}z), \quad \omega_1 = \sqrt{1 + A_1 z^2} F_1, \quad \omega_2 = \sqrt{1 + A_1 z^2} F_2, \quad (18)$$

(14),(15) 式变换为

$$\frac{d^2 F_1}{du^2} + b^2 F_1 = \frac{B_1}{A_1} \left[(1 - Q_1) \frac{F_2}{F_1} - 4Q_2 \frac{F_2/F_1}{(1 + \omega_{12}^2 F_2^2 / (\omega_{11}^2 F_1^2))^2} \right] \frac{1}{F_2 F_1^2}, \quad (19)$$

$$\frac{d^2 F_2}{du^2} + b^2 F_2 = \frac{B_2}{A_1} \left[(1 - Q_2) \frac{F_1}{F_2} - 4Q_1 \frac{F_1/F_2}{(1 + \omega_{11}^2 F_1^2 / (\omega_{12}^2 F_2^2))^2} \right] \frac{1}{F_1 F_2^2}, \quad (20)$$

式中 $b^2 = 1 + A_0/A_1$. 边界条件变换为

$$F_1(u)|_{u=0} = F_2(u)|_{u=0} = 1, \quad (21)$$

$$\frac{dF_1}{du} \Big|_{u=0} = \rho_{11}/\sqrt{A_1} = S_{11}, \quad \frac{dF_2}{du} \Big|_{u=0} = \rho_{12}/\sqrt{A_1} = S_{12}. \quad (22)$$

定义

$$G = Q_1 \omega_{11}^2 F_1^2 + Q_2 \omega_{12}^2 F_2^2, \quad (23)$$

结合 (19),(20) 式得

$$d^2G/du^2 = 4H, \quad dH/du = -b^2dG/du, \quad (24)$$

$$H = (1/2)\{Q_1\omega_{11}^2[(dF_1/du)^2 - b^2F_1^2 + (B_1/A_1)(1 - Q_1)/F_1^2] + Q_2\omega_{12}^2[(dF_2/du)^2 - b^2F_2^2 + (B_2/A_1)(1 - Q_2)/F_2^2] - 16Q_1Q_2/[A_1k^2(\omega_{11}^2F_1^2 + \omega_{12}^2F_2^2)]\}. \quad (25)$$

由 (21),(22),(24) 式得

$$H = -b^2G + D_1, \quad d^2G/du^2 + 4b^2G = 4D_1, \quad (26)$$

$$D_1 = (1/2)\{b^2(Q_1\omega_{11}^2 + Q_2\omega_{12}^2) + Q_1\omega_{11}^2[S_{11}^2 + B_1(1 - Q_1)/A_1] + Q_2\omega_{12}^2[S_{12}^2 + B_2(1 - Q_2)/A_1] - 16Q_1Q_2/[A_1k^2(\omega_{11}^2 + \omega_{12}^2)]\}, \quad (27)$$

$$G = (Q_1\omega_{11}^2 + Q_2\omega_{12}^2 - D_1/b^2) \cos[2b \tan^{-1}(\sqrt{A_1}z)] + [(Q_1\omega_{11}^2S_{11} + Q_2\omega_{12}^2S_{12})/b] \sin[2b \tan^{-1}(\sqrt{A_1}z)] + D_1/b^2. \quad (28)$$

(19),(20) 式的不变量为^[13]

$$IV = (F_1dF_2/du - F_2dF_1/du)^2 + (1/A_1)\{B_1(1 - Q_1)F_2^2/F_1^2 + B_2(1 - Q_2)F_1^2/F_2^2 + 4B_1Q_2\omega_{11}^4F_1^2/[\omega_{12}^2(\omega_{11}^2F_1^2 + \omega_{12}^2F_2^2)] + 4B_2Q_1\omega_{12}^4F_2^2/[\omega_{11}^2(\omega_{11}^2F_1^2 + \omega_{12}^2F_2^2)]\}. \quad (29)$$

(23) 式引入极坐标

$$\sqrt{Q_1}\omega_{11}F_1 = \sqrt{G} \cos \theta, \quad \sqrt{Q_2}\omega_{12}F_2 = \sqrt{G} \sin \theta, \quad (30)$$

代入 (29) 式, 并结合 (18),(21),(22) 式得

$$\frac{d\theta}{\sqrt{D_2 - T(\theta)}} = \frac{\sqrt{A_1}dz}{(1 + A_1z^2)G}, \quad \tan \theta_0 = \frac{\omega_{12}}{\omega_{11}} \sqrt{Q_2/Q_1}, \quad (31)$$

$$T(\theta) = [4/(A_1k^2)]\{(1 - Q_1)Q_1^2 \tan^2 \theta + (1 - Q_2)Q_2^2 \cot^2 \theta + 4Q_1Q_2(Q_1^2 \tan^2 \theta + Q_2^2)/(Q_1 \tan^2 \theta + Q_2)\}, \quad (32)$$

$$D_2 = [4/(A_1k^2)]\{(1 - Q_1)Q_1^2 \tan^2 \theta_0 + (1 - Q_2)Q_2^2 \cot^2 \theta_0 + 4Q_1Q_2(Q_1^2 \tan^2 \theta_0 + Q_2^2)/(Q_1 \tan^2 \theta_0 + Q_2)\} + Q_1Q_2\omega_{11}^2\omega_{12}^2(S_{11} - S_{12})^2. \quad (33)$$

(31) 式的变量已分离. 由 (31),(28),(30),(18) 式即可得到 ω_1, ω_2 , 求解了 (14),(15) 式. 由 (16) 式得棒内光束波前曲率半径的倒数:

$$\rho_1 = \frac{A_1z}{1 + A_1z^2} + \frac{1}{2G} \frac{dG}{dz} - \tan \theta \frac{d\theta}{dz}, \quad \rho_2 = \frac{A_1z}{1 + A_1z^2} + \frac{1}{2G} \frac{dG}{dz} + \cot \theta \frac{d\theta}{dz}. \quad (34)$$

3 高斯光束的物象变换

两光束经棒透镜的物象变换分别为^[4-7]

$$L_1 = -\pi^2 n_{co} \omega_{11}^4 \omega_1^4(Z) \rho_1(Z) / [\pi^2 n_{co}^2 \omega_{11}^4 \omega_1^4(Z) \rho_1^2(Z) + \lambda^2], \quad (35)$$

$$L_2 = -\pi^2 n_{co} \omega_{12}^4 \omega_2^4(Z) \rho_2(Z) / [\pi^2 n_{co}^2 \omega_{12}^4 \omega_2^4(Z) \rho_2^2(Z) + \lambda^2], \quad (36)$$

式中 Z 为棒长. 出射光束的束腰半径分别为^[4-7]

$$\omega_{31} = \sqrt{\lambda^2 L_1^2 + \pi^2 \omega_{11}^4 \omega_1^4(Z) [1 + n_{co} \rho_1(Z) L_1]^2} / [\pi \omega_{11} \omega_1(Z)], \quad (37)$$

$$\omega_{32} = \sqrt{\lambda^2 L_2^2 + \pi^2 \omega_{12}^4 \omega_2^4(Z) [1 + n_{co} \rho_2(Z) L_2]^2} / [\pi \omega_{12} \omega_2(Z)], \quad (38)$$

放大率分别为

$$M_1 = \omega_{31} / \omega_{01}, \quad M_2 = \omega_{32} / \omega_{02}. \quad (39)$$

4 计算实例和讨论

(14),(15),(16) 式的解给出了两正交极化高斯光束在棒中的传播规律和光场特性. 以下分两种情况讨论光束在棒中的传播过程.

(1) 自聚焦. 令 (28) 式 $G = 0$, 可得到使光束坍塌的光束功率. 以简单情况为例, 若 $\omega_{11} = \omega_{12}$, $\rho_{11} = \rho_{12}$, 当光束的归一化功率达

$$Q_1 + Q_2 = 1 - \frac{b^2 A_1}{B_1} + \frac{S_{11}^2 A_1}{B_1} + 2 \frac{b A_1}{B_1} \frac{b + S_{11} \sin[2b \tan^{-1}(\sqrt{A_1} Z')]}{1 - \cos[2b \tan^{-1}(\sqrt{A_1} Z')]} \quad (40)$$

时, 两光束传播过程产生自聚焦, 并在 $z = Z'$ 处坍塌, 即 $\omega_1(Z') = \omega_2(Z') = 0$. 若 $\omega_{11} \neq \omega_{12}$, 引入参数 $q = \omega_{11} / \omega_{12}$, 考虑简单情况 $Q = Q_1 = Q_2$, 当光束的归一化功率达

$$Q = \frac{(q^2 + 1)^2 q^2}{q^4 + 6q^2 + 1} \left\{ \frac{1}{q^2} - \frac{b^2 A_1}{B_2} + \frac{(q^2 S_{11}^2 + S_{12}^2) A_1}{B_2 (q^2 + 1)} + \frac{1}{B_2} \frac{2b^2 A_1}{1 - \cos[2b \tan^{-1}(\sqrt{A_1} Z')]} \right. \\ \left. + \frac{2b(q^2 S_{11} + S_{12}) A_1}{B_2 (q^2 + 1)} \frac{\sin[2b \tan^{-1}(\sqrt{A_1} Z')]}{1 - \cos[2b \tan^{-1}(\sqrt{A_1} Z')]} \right\} \quad (41)$$

时, $\omega_1(Z') = \omega_2(Z') = 0$, 两光束在 $z = Z'$ 处坍塌. 若 $\omega_{11} \neq \omega_{12}$, $Q_1 \neq Q_2$, 总存在两归一化功率 Q_1 和 Q_2 , 使两光束在某个 Z' 处坍塌.

(2) 增束宽振荡. 当光束功率不足以使光束坍塌时, 光束将作束宽逐渐增大的振荡传播, 即 ω_1 和 ω_2 为 z 的振荡函数, 幅度随 z 逐渐增大.

图 3 至图 6 的计算中, 一些参数取典型值: $n_{co} = 1.6$, $\lambda = 1.55 \mu\text{m}$, $A_1 = 0.01 \text{mm}^{-2}$, $A_0 = 0.2 \text{mm}^{-2}$, 两入射光束的束腰半径分别取 $\omega_{01} = 10\lambda$ 和 $\omega_{02} = 35\lambda$. 图 3 和图 4 分别为束腰位置在 $L_{01} = 0.5 \text{mm}$ 和 $L_{02} = 1.5 \text{mm}$ 处的两入射光束经棒透镜变换, 出射后束腰位置 L_1 和 L_2 (象距) 与棒长 Z 的关系. 图 3 中, $L_1 < 0$, 出射光束为虚束腰, 具有凹透镜特征; 当 $Z > 0.17 \text{mm}$ 时, $L_2 > 0$, 为实束腰, 具有凸透镜性质. 图 4 中, 在 $Z = 3.66 \text{mm}$ 处, $L_1 = L_2 = 0$, 此时还有 $M_1 = M_2 = 0$, 表明光束在 $Z = 3.66 \text{mm}$ 处坍塌 ($\omega_1(Z) = \omega_2(Z) = 0$), 在实际使用时应避免光束坍塌损坏透镜. 而在图 3 的 $Z = 0.17 \text{mm}$ 处, $L_2 = 0$, 出射光束的束腰恰好位于棒的出射端面, 但 M_1 和 $M_2 \neq 0$, 没有塌束. 图 3 和图 4 仅参数 Q_2 不同, 分别为 0.35 和 1.85, Q_1 都为 0.45, 表明两束光在非线性媒质中由于非线性相互作用, 一束光的光束功率对自己和另一束光的传播和物象变换有显著影响.

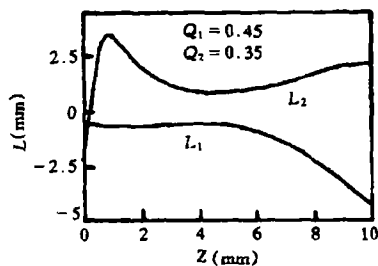
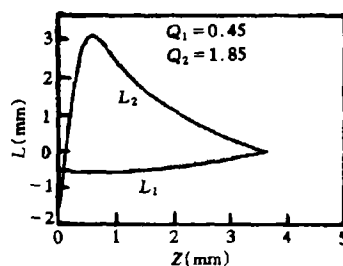
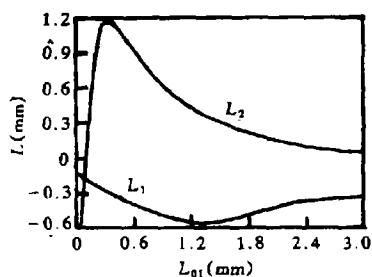
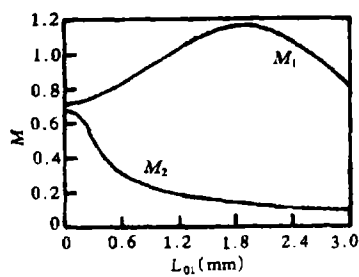
图 3 象距 L_1 和 L_2 与棒长 Z 的关系图 4 象距 L_1 和 L_2 与棒长 Z 的关系

图 5 和图 6 分别为透镜长 $Z = 4.5\text{mm}$, $Q_1=0.45$, $Q_2=0.35$, 一物距 $L_{02} = 1.5\text{mm}$ 为常数时, 象距 L_1 和 L_2 , 放大率 M_1 和 M_2 与一光束物距 L_{01} 的关系. 图 5 中 $L_1 < 0$, 出射时为虚束腰; $L_{01} > 0.086\text{mm}$ 时, $L_2 > 0$, 出射光束为实束腰. 图 6 中 M_1 在一些区域大于 1, 在另外一些区域小于 1. 一光束的束腰位置对两光束经棒透镜的物象变换有显著影响.

计算结果还表明入射光束的束腰半径对两光束的光场和经棒透镜的物象变换也有显著影响.

图 5 象距 L_1 和 L_2 与物距 L_{01} 的关系图 6 放大率 M_1 和 M_2 与物距 L_{01} 的关系

5 结束语

分析结果表明, 两正交极化高斯光束在克尔非线性倒抛物型梯度折射率棒透镜内有两种传播方式: 自聚焦(坍塌)和增束宽振荡. 一束光的参数对自己和另一束光在棒中的传播和经棒透镜的物象变换有显著影响和控制作用.

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OBJECT-IMAGE TRANSFORMATION OF TWO ORTHOGONALLY POLARIZED OPTICAL BEAMS IN A NONLINEAR REVERSAL PARABOLIC GRADED-INDEX ROD LENS

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Abstract The nonlinear coupled differential equations of dimensionless beam width parameters of two Gaussian optical beams with orthogonal polarization in a family of Kerr-law nonlinear reversal parabolic graded-index rod lenses are derived by using a variational approach based on the scalar Maxwell's equations and then solved. The characteristics of fields in the rod lens and object-image transformation through the rod lens of two orthogonally polarized optical beams are investigated.

Key words Graded-index, Rod lens, Imaging

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