粗糙面激光脉冲非相干散射及强度起伏协方差函数

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摘要 基于激光脉冲粗糙面散射特征, 利用积分变换, 误差函数和随机变量的统计矩, 研究激光脉冲非相干散射和散射场量的强度起伏协方差函数特征. 在入射激光波长 $\lambda = 1.06 \mu\text{m}$ 条件下, 数值计算了不同粗糙面高度起伏均方和相关长度, 不同入射角等影响因素下, 散射场相干和非相干分量, 以及强度起伏协方差函数随散射角和相干带宽频差的变化情况. 计算结果表明, 在激光脉冲入射下, 随机粗糙面的高度均方越小, 相关长度越大, 即表面越光滑, 散射场的相干和非相干分量在入射角镜反射方向出现最大峰值, 非相干分量峰值在非入射角镜反射方向上会迅速减小, 且非相干分量在量级比相干散射分量上小很多, 散射场强度起伏协方差函数的分布趋势随着相干带宽频差的增大逐步减小, 镜反射方向和相干带宽频差为零时出现最大峰值. 本文所给出的研究结果, 深化了粗糙面脉冲散射场量的四阶统计特征, 为开展目标激光脉冲散射场量高阶统计特征和激光散斑探测研究奠定基础.

关键词

粗糙面散射
脉冲散射
四阶矩统计特征
非相干散射特征
强度起伏
协方差函数

粗糙面及粗糙体目标散射的特性研究在各个国家国防、军事航天及民用领域都有显著的学术价值和广泛的应用背景, 目标光(电)特性的研究自20世纪50年代起一直是充满活力的课题^[1~5]. 激光器的研制, 有关目标散射特征的研究从电磁波段扩展到了光波段^[6]. Wu等人^[7]采用物理光学近似研究了任意形状粗糙物体对激光的散射特征. Ishimaru等人^[8,9]从理论和试验上开展了随机粗糙面脉冲波散射研究工作, 讨论粗糙面脉冲展宽, 后向散射增强效应.

针对脉冲波散射二阶矩、四阶矩, 或者高阶统计特性研究, 人们主要集中在随机介质与电磁波散射领域^[10~14]. 当入射电磁波随着波长减小, 进入光学波段时, 关于光波散射四阶或者高阶矩问题人们也主要集中在随机介质对光波散射特性研究上, 如通

过研究光波在大气湍流中传播场量的三阶、四阶或者高阶统计特征, 讨论光强度分布, 相位起伏、闪烁, 物像能谱分布等^[10~16].

关于粗糙面散射四阶或者高阶统计特性的研究, 国内外公开发表的文献还比较少, Tsang等人^[17]给出了一维高斯粗糙面平面波散射场四阶的理论表达式, 并给出了四阶矩频谱的推导方法, 王明军等人^[18]研究了激光脉冲入射下粗糙面散射四阶统计特征. Goodman^[19,20]系统研究了光波的统计特性, 以及其在激光散斑中的应用. 王明军等人^[21]将平面波用高斯波束替代, 研究其二阶随机粗糙面散射强度互相干等四阶统计特性. 随机粗糙面散射场量高阶统计特征与激光散斑直接相关, 对目标激光散斑探测, 激光“噪声”提取提供重要的理论支撑^[19~23].

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本文基于上述文献和前期工作基础,着力于研究当激光脉冲波入射下,不同高度起伏和相关长度,不同入射角,不同相关带宽频差,相干和非相干散射分量、强度起伏协方差函数随散射角和相关频差的变化关系,重点分析了非相干分量,强度起伏协方差函数的变化特征.本文所做的工作继续深化散射场量的四阶矩统计特征,对随机粗糙面散射场量高阶统计特征研究提供了预先理论基础.

1 激光脉冲非相干散射及其强度起伏协方差函数

假定一维随机粗糙面高度起伏 $z=f(x)$,根据A Ishimaru粗糙面散射理论,在基尔霍夫近似条件下,其粗糙面远区散射场为^[1,5,9,10]

$$\bar{E}_s = k \cos \theta_s \sqrt{\frac{2\pi}{kR}} e^{i(kR - \pi/4)} T(\bar{k}_i, \bar{k}_s), \quad (1)$$

式中 $k=2\pi/\lambda$ 为入射波数, θ_s 为散射角, R 为远区散射场点到坐标原点的距离,传输矩阵 $T(\bar{k}_i, \bar{k}_s)$,粗糙面被照射尺度为 L 的区域内,粗糙面双频散射系数可写成

$$\sigma_0 = 2\pi\sqrt{kk'} \cos \theta \cos \theta' \langle (T_f T_f'^*) / L \rangle e^{i(\bar{k} - \bar{k}') \cdot R}, \quad (2)$$

其中 $T = T(\bar{k}_s, \bar{k}_i) = \langle T \rangle + T_f$, $T' = T'(\bar{k}_s, \bar{k}_i) = \langle T' \rangle + T_f'$, $\langle T \rangle$ 表示相干部分, T_f 表示非相干部分. (2)式中的 $\langle T_f(\omega) T_f'^*(\omega') \rangle$ 称为双频互相干函数,写成如下形式:

$$\begin{aligned} \langle T T'^* \rangle &= H_1' H_1 \int dx_1 \int dx_1' [\langle \exp(-i\vec{\nu} \cdot \vec{r}_1 + i\vec{\nu}' \cdot \vec{r}_1') \rangle \\ &\quad - \langle \exp(-i\vec{\nu} \cdot \vec{r}_1) \rangle \langle \exp(i\vec{\nu}' \cdot \vec{r}_1') \rangle]. \end{aligned} \quad (3)$$

下面将利用数理统计特征,详细推导激光脉冲非相干散射及其强度起伏协方差函数.根据协方差函数定义^[24],

$$C_i(r_1, r_2) = \langle I(r_1) I(r_2) \rangle - \langle I(r_1) \rangle \langle I(r_2) \rangle, \quad (4)$$

激光脉冲散射强度起伏协方差统计特征可表示为

$$\begin{aligned} C_{if}(r_1, r_2) &= \langle I_{sf}(r_1) I_{sf}(r_2) \rangle - \langle I_{sf}(r_1) \rangle \langle I_{sf}(r_2) \rangle \\ &= \langle E_{sf}^s(r_1, \omega_1) E_{sf}^{s*}(r_1, \omega_1) E_{sf}^s(r_2, \omega_2) E_{sf}^{s*}(r_2, \omega_2) \rangle \\ &\quad - \langle E_{sf}^s(r_1, \omega_1) E_{sf}^{s*}(r_1, \omega_1) \rangle \langle E_{sf}^s(r_2, \omega_2) E_{sf}^{s*}(r_2, \omega_2) \rangle. \end{aligned} \quad (5)$$

按照随机过程统计量的定义,在(5)中因式 $\langle E_{sf}^s(r_1, \omega_1) E_{sf}^{s*}(r_1, \omega_1) \rangle \langle E_{sf}^s(r_2, \omega_2) E_{sf}^{s*}(r_2, \omega_2) \rangle$ 定义为双点双频四阶统计特征函数,在高斯随机过程条件下,令

$$\begin{aligned} \Gamma_{2,2}(r_1, r_2; \omega_1, \omega_2) \\ = \langle E_{sf}^s(r_1, \omega_1) E_{sf}^{s*}(r_1, \omega_1) E_{sf}^s(r_2, \omega_2) E_{sf}^{s*}(r_2, \omega_2) \rangle, \end{aligned} \quad (6)$$

将其展开为

$$\begin{aligned} \Gamma_{2,2}(r_1, r_2; \omega_1, \omega_2) \\ = \langle E_{sf}^s(r_1, \omega_1) E_{sf}^s(r_2, \omega_2) \rangle \langle E_{sf}^{s*}(r_1, \omega_1) E_{sf}^{s*}(r_2, \omega_2) \rangle \\ + \langle E_{sf}^s(r_1, \omega_1) E_{sf}^{s*}(r_2, \omega_2) \rangle \langle E_{sf}^{s*}(r_1, \omega_1) E_{sf}^s(r_2, \omega_2) \rangle \\ + \langle E_{sf}^s(r_1, \omega_1) E_{sf}^{s*}(r_1, \omega_1) \rangle \langle E_{sf}^s(r_2, \omega_2) E_{sf}^{s*}(r_2, \omega_2) \rangle, \end{aligned} \quad (7)$$

将(7)式带入(5)式得

$$\begin{aligned} C_{if}(r_1, r_2) \\ = \Gamma_{2,2}(r_1, r_2; \omega_1, \omega_2) - \left| \langle E_{sf}^s(r_1, \omega_1) \rangle \right|^2 \left| \langle E_{sf}^s(r_2, \omega_2) \rangle \right|^2 \\ = \langle E_{sf}^s(r_1, \omega_1) E_{pq}^s(r_2, \omega_2) \rangle \langle E_{sf}^{s*}(r_1, \omega_1) E_{pq}^{s*}(r_2, \omega_2) \rangle \\ + \langle E_{sf}^s(r_1, \omega_1) E_{pq}^{s*}(r_2, \omega_2) \rangle \langle E_{sf}^{s*}(r_1, \omega_1) E_{pq}^s(r_2, \omega_2) \rangle. \end{aligned} \quad (8)$$

对于随机粗糙面激光脉冲的双点散射场量的几何关系如图1所示,散射点 r_1, r_2 对应散射场:

$$\begin{aligned} \bar{E}_{s1} &= \bar{E}_{s1}(k_{i1}, k_{s1}) = \langle \bar{E}_{s1} \rangle + \bar{E}_{sf1}, \\ \bar{E}_{s2} &= \bar{E}_{s2}(k_{i2}, k_{s2}) = \langle \bar{E}_{s2} \rangle + \bar{E}_{sf2}. \end{aligned} \quad (9)$$

波矢量满足如下关系式:

$$\begin{aligned} \bar{k}_{i1} &= k_1 \sin \theta_i \bar{x} - k_1 \cos \theta_i \bar{z}, \\ \bar{k}_{s1} &= k_1 \sin \theta_s \bar{x} + k_1 \cos \theta_s \bar{z}, \\ \bar{k}_{i2} &= k_2 \sin \theta_i \bar{x} + k_2 \cos \theta_i \bar{z}, \\ \bar{k}_{s2} &= k_2 \sin \theta_s \bar{x} - k_2 \cos \theta_s \bar{z}. \end{aligned} \quad (10)$$

结合(3)和(8)式, (5)式将变成

$$\begin{aligned} C_{if}(r_1, r_2) \\ = \langle T_1(k_{s1}, k_{i1}) T_2^*(k_{s2}, k_{i2}) \rangle \langle T_1^*(k_{s1}, k_{i1}) T_2(k_{s2}, k_{i2}) \rangle \\ + \langle T_1(k_{s1}, k_{i1}) T_2(k_{s2}, k_{i2}) \rangle \langle T_1^*(k_{s1}, k_{i1}) T_2^*(k_{s2}, k_{i2}) \rangle, \end{aligned} \quad (11)$$

其中(11)式中各项展开为

图1 一维随机粗糙面激光散射几何示意图

Figure 1 Geometrical relations of laser scattering from one-dimensional random rough surface

$$\begin{aligned}
& \langle T_1(k_{s1}, k_{i1}) T_2^*(k_{s2}, k_{i2}) \rangle \\
&= H_1 H_2 \int dx_1 \int dx_2 [\langle \exp(-i\vec{v}_1 \cdot \vec{r}_1 + i\vec{v}_2 \cdot \vec{r}_2) \rangle \\
&\quad - \langle \exp(-i\vec{v}_1 \cdot \vec{r}_1) \rangle \langle \exp(i\vec{v}_2 \cdot \vec{r}_2) \rangle] \\
& \langle T_1^*(k_{s1}, k_{i1}) T_2(k_{s2}, k_{i2}) \rangle \\
&= H_1 H_2 \int dx_1 \int dx_2 [\langle \exp(i\vec{v}_1 \cdot \vec{r}_1 - i\vec{v}_2 \cdot \vec{r}_2) \rangle \\
&\quad - \langle \exp(i\vec{v}_1 \cdot \vec{r}_1) \rangle \langle \exp(-i\vec{v}_2 \cdot \vec{r}_2) \rangle] \\
& \langle T_1(k_{s1}, k_{i1}) T_2(k_{s2}, k_{i2}) \rangle \\
&= H_1 H_2 \int dx_1 \int dx_2 [\langle \exp(-i\vec{v}_1 \cdot \vec{r}_1 - i\vec{v}_2 \cdot \vec{r}_2) \rangle \\
&\quad - \langle \exp(-i\vec{v}_1 \cdot \vec{r}_1) \rangle \langle \exp(-i\vec{v}_2 \cdot \vec{r}_2) \rangle] \\
& \langle T_1^*(k_{s1}, k_{i1}) T_2^*(k_{s2}, k_{i2}) \rangle \\
&= H_1 H_2 \int dx_1 \int dx_2 [\langle \exp(i\vec{v}_1 \cdot \vec{r}_1 + i\vec{v}_2 \cdot \vec{r}_2) \rangle \\
&\quad - \langle \exp(i\vec{v}_1 \cdot \vec{r}_1) \rangle \langle \exp(i\vec{v}_2 \cdot \vec{r}_2) \rangle]. \quad (12)
\end{aligned}$$

把(12)式中每一项详细推导[见附录(A1)~(A14)式], 带入(11)式整理后, 得到激光脉冲入射下, 强度起伏非相干散射协方差函数统计特征表示

$$\begin{aligned}
C_{if}(r_1, r_2) &= [H_1 H_2 \Phi_{s12}^* \Phi_{i2}^*][H_1 H_2 \Phi_{s1'2} \Phi_{i'2}] \\
&\quad + [H_1 H_2 \Phi_{s12} \Phi_{i2}][H_1 H_2 \Phi_{s1'2}^* \Phi_{i'2}^*] \\
&= \frac{F_1 R_1 F_2 R_2}{4\pi^2} \cdot \left\{ \left[\frac{\sin(\nu_{d12} L / 2)}{\nu_{d12} L / 2} \right]^2 \right. \\
&\quad \times \left[\exp\left[-(\nu_{z1} - \nu_{z2})^2 \sigma^2 / 2\right] \sqrt{\frac{\pi}{\nu_{z1} \nu_{z2}}} \right. \\
&\quad \times \left. \left(\frac{l}{\sigma} \right) \exp(-\nu_{c12}^2 l^2 / 4 \nu_{z1} \nu_{z2} \sigma^2) \right]^2 \\
&\quad + \left[\frac{\sin(\nu_{c12} L)}{\nu_{c12} L} \right]^2 \cdot \left\{ \sqrt{\frac{\pi}{2}} L \cdot \exp(-\nu_{d12}^2 L^2 / 8) \right. \\
&\quad \times \exp[-(\nu_{z1} + \nu_{z2})^2 / 2] \cdot \left\{ 2 + [\exp(-\nu_{z1} \nu_{z2} \sigma^2) - 1] \right. \\
&\quad \times \left. \left[\operatorname{erf}\left(\frac{2x_0 + iL^2 \nu_{d12}}{2\sqrt{2}L}\right) - \operatorname{erf}\left(\frac{-2x_0 + iL^2 \nu_{d12}}{2\sqrt{2}L}\right) \right] \right\} \left. \right\} \left. \right\}, \quad (13)
\end{aligned}$$

式中 $\operatorname{erf}(\dots)$ 为误差函数。

2 激光脉冲非相干散射及其强度起伏协方差函数的数值计算和分析

依据(12), (13)式和附录(A1)~(A14)式给出的解析表达式, 本节将通过数值方法, 详细计算和分析了各种不同粗糙面和入射角对其激光脉冲相干、非相干散射和强度起伏高度起伏的影响。数值计算条件: 入

射激光波长 $\lambda = 1.06 \text{ m}$ 照射尺度 $L = 200\lambda$, 粗糙面高度起伏均方 $\sigma \leq \lambda$, 相关长度 $l \leq 12\lambda$, 两个散射点间的相干带宽频差 $f_d = 0 \sim 80 \times 10^{12} \text{ Hz}$ 。

图2给出了不同高度起伏均方差和入射角, 相干散射分量 $\langle TT^* \rangle$ 随散射角变化情况, 其中 $f_d = 0 \text{ Hz}$, 入射角为 $\theta_i = 0^\circ, 20^\circ, 40^\circ$, 相干长度 $l = 12\lambda$, 粗糙面高度起伏均方 $\sigma = 0.3\lambda, 0.6\lambda, 0.9\lambda$ 。 $\theta_i = 0^\circ, \sigma = 0.6\lambda, \theta_i = 20^\circ, \sigma = 0.9\lambda, \theta_i = 40^\circ$ 。计算结果表明, 粗糙面高度起伏均方对相干散射分量 $\langle TT^* \rangle$ 有影响, 在镜向(即入射的反射方向上)出现峰值, 且随着粗糙面高度起伏均方的增加相干分量而减小。

图3计算了不同粗糙面高度起伏均方、入射角, 非相干散射分量 $\langle T_1 T_2 \rangle$ 随散射的变化情况, 数值计算条件和图2相同, 比较图2计算结果, 可以看出, 和相干散射分量一样, 在镜向反射方向出现会峰值, 相比相干散射, 非相干散射在非镜向方向很快衰减为零, 并且非散射分量和相干散射分量相比小很多, 相干分量是散射光强的主要部分。相同粗糙面相干长度条件下, 粗糙度均方高度对非相干散射的影响也很强。

图4计算了不同粗糙面高度起伏均方、入射角, 强度起伏协方差函数 $C_{if}(r_1, r_2)$ 随散射角的变化情况, 数值计算的条件和图2和图3相同。强度起伏协方差函数 $C_{if}(r_1, r_2)$ 受粗糙面高度起伏均方的影响很大, 在镜向反射方向上, 随着粗糙面高度起伏均方的增加 $C_{if}(r_1, r_2)$ 而会逐渐减小, 并且随着散射角的变化, 其分布趋势上和相干散射分量的曲线相同。

图5(a)将在图4基础上, 改变计算条件, 给出不同入射角, 强度起伏协方差函数 $C_{if}(r_1, r_2)$ 随相干带宽频差的变化情况。入射角为 $\theta_i = 0^\circ$ 时(垂直粗糙面入

图2 (网络版彩色)相干散射分量 $\langle TT^* \rangle$ 随入射角变化的情况

Figure 2 (Color online) The coherent scattering components $\langle TT^* \rangle$ are changed with scattering angles

图3 不同入射角 θ_i 和高度起伏均方 σ 非起伏项 $\langle T_1 T_2 \rangle$ 随散射角的变化情况. (a) $\theta_i = 0^\circ, \sigma = 0.3\lambda$; (b) $\theta_i = 20^\circ, \sigma = 0.6\lambda$; (c) $\theta_i = 40^\circ, \sigma = 0.9\lambda$

Figure 3 The incoherent scattering components $\langle T_1 T_2 \rangle$ are changed with scattering angles in different incidence angles θ_i and fluctuating heights σ . (a) $\theta_i = 0^\circ, \sigma = 0.3\lambda$; (b) $\theta_i = 20^\circ, \sigma = 0.6\lambda$; (c) $\theta_i = 40^\circ, \sigma = 0.9\lambda$

图4 (网络版彩色)强度起伏协方差函数随散射角的变化情况

Figure 4 (Color online) The covariance function of the scattered intensity fluctuation versus scattering angles

图5 (网络版彩色)强度起伏协方差函数随相干带宽频差的变化情况. (a) 不同入射角; (b) 不同相干长度

Figure 5 (Color online) The covariance function of the scattered intensity fluctuation versus in the different incidence angles (a) and different coherence length (b)

射), 粗糙面高度起伏 $\sigma = 0.6\lambda$ 和相干长度 $l = 12\lambda$, 散射角为, $\theta_s = 0^\circ, \theta_s = 5^\circ, \theta_s = 10^\circ, \theta_s = 20^\circ$. 从图5中可以看出, 当粗糙面参数不变, 入射角一定的情况下, 强度起伏协方差函数在镜向方向散射仍然最强, 在非镜反射方向, 其值将逐步减弱. 让高度起伏均方 $\sigma = 0.6\lambda$ 不变, 改变粗糙面相干长度 $l = 3\lambda, l = 6\lambda, l = 9\lambda, l = 12\lambda$, 图5(b)给出了不同相关长度, 强度起伏协方差函数 $C_{if}(r_1, r_2)$ 随散射角的变化情况, 其中相干带宽频差 $f_d = 0$ Hz, 散射角 $\theta_s = 0^\circ$, 入射角为 $\theta_i = 0^\circ$, 计算结果表明, 粗糙度一定情况下, 相干长度越大强度起伏协方差函数的值也越大, 并随着频差增大, 其值逐步减小. 图6和7给出了强度起伏协方差函数随散射角和相干带宽频差的总的变化趋势. 图6(a) ~ (d) 分别表示的是入射角为 $\theta_i = 0^\circ$, 粗糙面高度起伏均方 $\sigma = 0.6\lambda$ 时, 相干长度 $l = 3\lambda, 6\lambda, 9\lambda, 12\lambda$, 强度起伏协方差函数随相干带宽频差和散射角变化情况. 从分布趋势的可以看出, 相关长度对强度起伏协方差函数 $C_{if}(r_1, r_2)$ 的影响并不是很明显, 改变相关长度, $C_{if}(r_1, r_2)$ 的曲线轮廓基本

图6 (网络版彩色)不同相关长度强度起伏协方差函数随相干带宽频差和散射角的变化情况. (a) $l=3\lambda$; (b) $l=6\lambda$; (c) $l=9\lambda$; (d) $l=12\lambda$

Figure 6 (Color online) The covariance function of the scattered intensity fluctuation are changed with coherence bandwidth and scattering angles in the different coherence lengths. (a) $l=3\lambda$; (b) $l=6\lambda$; (c) $l=9\lambda$; (d) $l=12\lambda$

相似, 相关长度越大, $C_{ij}(r_1, r_2)$ 的峰值都出现在镜向反射和相干频差为零处, 并随着相干长度的增大(粗糙面越光滑), $C_{ij}(r_1, r_2)$ 的峰值明显增大, 散射的能量越集中. 图7(a)~(d)从另外一个角度, 数值计算了强度起伏协方差函数 $C_{ij}(r_1, r_2)$ 不同粗糙面高度起伏均方 $\sigma = 0.2\lambda$, $\sigma = 0.4\lambda$, $\sigma = 0.6\lambda$, $\sigma = 0.8\lambda$ ($\sigma \leq \lambda$), 入射角 $\theta_i = 0^\circ$, 在相干长度 $l=6\lambda$ 的情况下, 强度起伏协方差函数 $C_{ij}(r_1, r_2)$ 随散射角和相干频差的变化情况. 从图中可以看出, 当粗糙面高度起伏均方增大时(粗糙度增加后) $C_{ij}(r_1, r_2)$ 值随着相干带宽频差和散射角逐渐变小, 总体上还是在镜向(即入射角为 0° 时)出现峰值, 而对于大的粗糙面高度起伏均方, $C_{ij}(r_1, r_2)$ 衰落的快.

3 结论

本文依据激光脉冲入射下随机介质粗糙面散射特征, 利用数理统计相关函数、统计矩和变量替换,

推导了散射场量强度起伏协方差函数的统计特征. 在入射激光波长 $\lambda=1.06 \mu\text{m}$, 论文利用高斯随机过程矩定理和激光脉冲散射特征, 创新性研究了不同粗糙面高度起伏和相关长度, 不同入射角, 不同相关频差等各种影响因素下, 强度起伏协方差和非相干散射分量随散射角和相干带宽频差的变化情况. 通过计算得到如下结论: (1) 相对与相干散射分量, 非相干散射分量在量级上要小很多, 粗糙面越光滑, 激光脉冲非相干分量越小, 非相干散射分量在非镜向方向上迅速减小. (2) 入射角度一定的情况下, 强度起伏协方差函数在镜反射方向会出现最大值, 粗糙面相干长度一定情况下, 粗糙面均方高度越小的, 峰值分量越大; 粗糙面均方高度一定情况下, 相干长度越大, 峰值分量越大. (3) 强度起伏协方差函数随相干带宽频差的增大和散射角变化趋势总体表现为粗糙面高度均方越小, 相关长度越大, 即表面越光滑, 强

图7 (网络版彩色)同相高度起伏均方强度起伏协方差函数随相干带宽频差和散射角的变化情况. (a) $\sigma = 0.2\lambda$; (b) $\sigma = 0.4\lambda$; (c) $\sigma = 0.6\lambda$; (d) $\sigma = 0.8\lambda$

Figure 7 (Color online) The covariance function of the scattered intensity fluctuation are changed with coherence bandwidth and scattering angles in different the mean of fluctuating heights. (a) $\sigma = 0.2\lambda$; (b) $\sigma = 0.4\lambda$; (c) $\sigma = 0.6\lambda$; (d) $\sigma = 0.8\lambda$

度起伏协方差函数在镜反射方向上出现最大值, 非入射角镜反射方向上迅速减弱, 强度起伏协方差函数峰值出现在相关频差为零和镜反射方向. 本文的

结果继续深化了粗糙面脉冲散射场量的四阶统计特征研究, 为开展目标激光脉冲散射场量高阶统计特征和激光散斑探测研究奠定基础.

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Laser pulse incoherence scattering characteristics and the covariance function of the scattered intensity fluctuation for a random rough surface

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According to the field characteristics of laser pulse scattering from a random rough surface, laser pulse incoherence scattering characteristics and a covariance function of the scattered intensity fluctuation are investigated numerically using the integral transform, an error function and the statistical moments of random variables. For an incident laser pulse, numerical methods are used to calculate the coherent and incoherent scattering characteristics and the covariance function of the fluctuation in scattering intensity with the coherence bandwidth frequency and scattering angle, considering multiple factors such as the mean of fluctuating heights, the coherence length of a random rough surface, and the incidence angle. Results show that for the incident laser pulse, a smaller mean of the fluctuating height and a longer correlation length correspond to a smoother surface and larger maximum peak values of coherent and incoherent scattering components in the specular direction. The incoherent scattering peak value decreases more rapidly in the non-specular direction, and incoherent scattering components are an order of magnitude smaller than coherent scattering components. The distribution of the covariance function of the scattering field intensity fluctuation gradually reduces with an increase in the coherence bandwidth frequency difference, having a maximum peak value in the specular direction as the coherence bandwidth difference tends to zero. This paper presents innovative results that emphasize the incoherent scattering characteristics and the covariance function of the scattered intensity fluctuation for the further study of the fourth-order moment statistical characteristic of laser pulse scattering from a rough surface. Future works investigate other high-order statistical moments of laser pulse scattering from a rough surface and laser speckle in laser detection applications.

scattering from rough surface, laser pulse scattering, the fourth order moment statistical characteristics, the incoherence scattering characteristics, the scattered intensity fluctuation, covariance function

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