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Target reconstruction algorithm for four-beam sheared coherent imaging

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四光束剪切相干成像目标重构算法研究

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针对传统剪切光束成像技术的准实时性问题, 提出用口字形排布的四束光代替传统L形三束剪切光照射目标, 研究了四光束剪切相干成像目标重构算法. 只需单次测量就能同时重构出四幅目标图像, 减少了用于降低散斑噪声、获取高质量图像所需的测量次数, 同时大大减少了多组发射时的光束切换次数, 提高了成像效率. 在算法实现中, 通过最小二乘法恢复出四组波前相位, 利用散斑幅值的简单代数运算恢复波前幅值, 从而重构出目标图像. 仿真结果表明, 与传统方法相比, 在图像质量相同的前提下, 本文方法所需的数据采集时间减少了至少1/2, 不但提高了目标重构效率, 还可为远程运动目标的成像识别提供更好的手段.

关键词: 剪切相干成像, 四光束, 目标重构, 成像效率

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1 引 言

剪切光束成像技术是一种非传统相干无透镜成像技术, 利用被测目标返回光束的散斑场进行计算成像, 在技术机理上能最大限度地克服大气湍流等扰动介质对成像分辨率的影响, 可实现对远距离目标的高分辨率成像. 该技术在远程暗弱目标监视、地形地貌观测、石油勘探及天文观测等领域有潜在的应用前景[1−3].

传统的剪切光束成像系统采用振幅干涉测量方法, 用三束在发射平面以L形排列的横向剪切同源激光同时照射目标[4−14], 三束激光的光频率稍有变化, 但波前几乎相同, 在目标上形成三个不同频差的拍频信号. 用探测器阵列接收从目标散射回来的调制光, 获得散斑强度和相位差信息, 进而计算重构出一幅目标图像. 将一系列这样的图像进行平均, 即可得到一幅质量较好的图像. 要进一步抑制大气湍流对成像的影响, 需发射多组三束相干光照射目标[11], 光束切换次数也会相应增多.

本文改进了传统剪切光束成像技术, 提出四光束剪切相干成像方法. 同时发射四束以口字形排布的激光照射目标, 等同于同时发射四组三光束激光对目标成像, 不但提高了成像效率, 而且达到单次多组发射的目的, 减小了大气湍流在最终成像中的影响. 利用快速傅里叶变换(FFT)提取四组散斑相位差和幅值, 通过迭代算法恢复目标频谱, 重构目标图像. 最后利用仿真验证了提出的四光束图像重构算法的有效性.

2 四光束剪切相干成像理论

图1为四光束剪切相干成像系统示意图, 发射四束空间位置、频率互不相同的口字形激光束照射目标, 产生四个形状相同且相互之间具有一定剪切量的散斑场, 并利用探测器阵列接收拍频回波信号. 利用FFT提取散斑相位差和强度, 重构四组波前, 通过傅里叶逆变换重构四幅目标图像.

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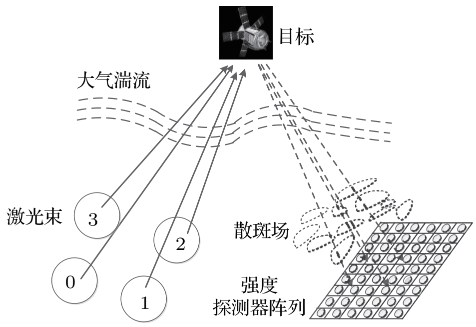

图1 四光束成像系统示意图

Fig. 1. Schematic of the four-beam imaging system.

发射平面与目标平面的几何关系如图2所示, 四束激光照射目标发生漫反射产生的散斑场在接收平面的分布为[5]

$$\begin{aligned}
& I_0(x,y,t) \\
&= E_0 A_0(u,v)\exp(-\mathrm{j}\omega_0 t)\exp[\mathrm{j}\phi(u,v)], \\
& I_1(x,y,t) \\
&= E_1 A_0[u+s_x/(\lambda R),v]\exp(-\mathrm{j}\omega_1 t) \\
&\quad\times \exp\{\mathrm{j}\phi[u+s_x/(\lambda R),v]\}, \\
& I_2(x,y,t) \\
&= E_2 A_0[u+s_x/(\lambda R),v+s_y/(\lambda R)]\exp(-\mathrm{j}\omega_2 t) \\
&\quad\times \exp\{\mathrm{j}\phi[u+s_x/(\lambda R),v+s_y/(\lambda R)]\}, \\
& I_3(x,y,t) \\
&= E_3 A_0[u,v+s_y/(\lambda R)]\exp(-\mathrm{j}\omega_3 t) \\
&\quad\times \exp\{\mathrm{j}\phi[u,v+s_y/(\lambda R)]\},
\end{aligned} \tag{1}$$

式中 $u = x/(\lambda R)$, $v = y/(\lambda R)$; E_i 和 ω_i 分别为第 i 束光的振幅和角频率; λ 为激光波长; R 为发射器与目标之间的距离; s_x, s_y 分别为横向、纵向剪切量; $A_0(u,v)$ 为波前幅值, $\phi(u,v)$ 为波前相位.

(1) 式中的四个散斑场发生干涉产生的拍频信号强度分布为

$$\begin{aligned}
I(x,y,t) &= |I_0+I_1+I_2+I_3|^2 \\
&= E_0^2A_0^2+E_1^2A_1^2+E_2^2A_2^2+E_3^2A_3^2 \\
&\quad + 2E_0E_1A_0A_1\cos(\Delta\omega_{01}t+\Delta\phi_{01}) \\
&\quad + 2E_0E_2A_0A_2\cos(\Delta\omega_{02}t+\Delta\phi_{02}) \\
&\quad + 2E_0E_3A_0A_3\cos(\Delta\omega_{03}t+\Delta\phi_{03}) \\
&\quad + 2E_1E_2A_1A_2\cos(\Delta\omega_{12}t+\Delta\phi_{12}) \\
&\quad + 2E_1E_3A_1A_3\cos(\Delta\omega_{13}t+\Delta\phi_{13}) \\
&\quad + 2E_2E_3A_2A_3\cos(\Delta\omega_{23}t+\Delta\phi_{23}),
\end{aligned} \tag{2}$$

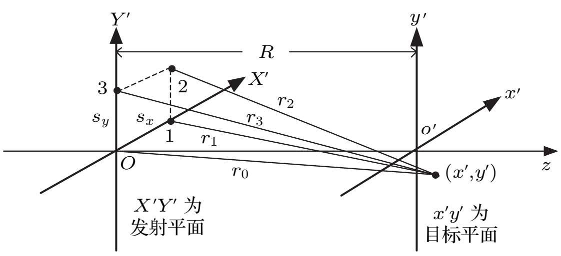

图2 发射平面与目标平面的几何关系

Fig. 2. Geometric relationship between transmitter plane and target plane.

式中

$$\begin{aligned}
A_0 &= A_0(u,v), \\
A_1 &= A_0[u+s_x/(\lambda R),v], \\
A_2 &= A_0[u+s_x/(\lambda R),v+s_y/(\lambda R)], \\
A_3 &= A_0[u,v+s_y/(\lambda R)],
\end{aligned}$$

$$\begin{aligned}
&\Delta\omega_{01}=\omega_1-\omega_0,\quad \Delta\omega_{02}=\omega_2-\omega_0, \\
&\Delta\omega_{03}=\omega_3-\omega_0,\quad \Delta\omega_{12}=\omega_2-\omega_1, \\
&\Delta\omega_{13}=\omega_3-\omega_1,\quad \Delta\omega_{23}=\omega_3-\omega_2, \\
&\Delta\phi_{01}=\phi(u,v)-\phi[u+s_x/(\lambda R),v], \\
&\Delta\phi_{02}=\phi(u,v)-\phi[u+s_x/(\lambda R),v+s_y/(\lambda R)], \\
&\Delta\phi_{03}=\phi(u,v)-\phi[u,v+s_y/(\lambda R)], \\
&\Delta\phi_{12}=\phi[u+s_x/(\lambda R),v] \\
&\qquad -\phi[u+s_x/(\lambda R),v+s_y/(\lambda R)], \\
&\Delta\phi_{13}=\phi[u+s_x/(\lambda R),v] \\
&\qquad -\phi[u,v+s_y/(\lambda R)], \\
&\Delta\phi_{23}=\phi[u+s_x/(\lambda R),v+s_y/(\lambda R)] \\
&\qquad -\phi[u,v+s_y/(\lambda R)].
\end{aligned}$$

由 (2) 式可知, 波前 $A_0(u,v)$ 和 $\phi(u,v)$ 隐含在散斑拍频信号中, 通过求解四组散斑相位差——$\Delta\phi_{01}$ 和 $\Delta\phi_{03}$, $\Delta\phi_{01}$ 和 $\Delta\phi_{12}$, $\Delta\phi_{12}$ 和 $\Delta\phi_{23}$, $\Delta\phi_{03}$ 和 $\Delta\phi_{23}$——可恢复四幅目标散斑图.

剪切相干成像的空间分辨率取决于探测器接收阵列最大间距 D, 可表示为 $\lambda R/D$. 当目标尺寸为 D_{obj}, 探测器间距应满足 $d \leqslant \frac{2}{3}\lambda R/D_{\mathrm{obj}}$ 的约束条件, 接收阵列单向维数 m 应满足 $m \geqslant D/d$ [15].

传统剪切光束成像技术发射三束光 (图1中的激光0, 1, 3), 产生三个散斑场, 单次测量只能重构一幅目标散斑图像[4−14]. 本文所述方法发射四束光, 可排列组合成四组散斑场 (三光束为一组), 等同于同时发射四组传统三光束激光 (图1中的激光0, 1, 3; 0, 1, 2; 1, 2, 3; 0, 2, 3) 对目标成像. 单次测量数据可同时重构出四幅目标散斑图像. 为获得

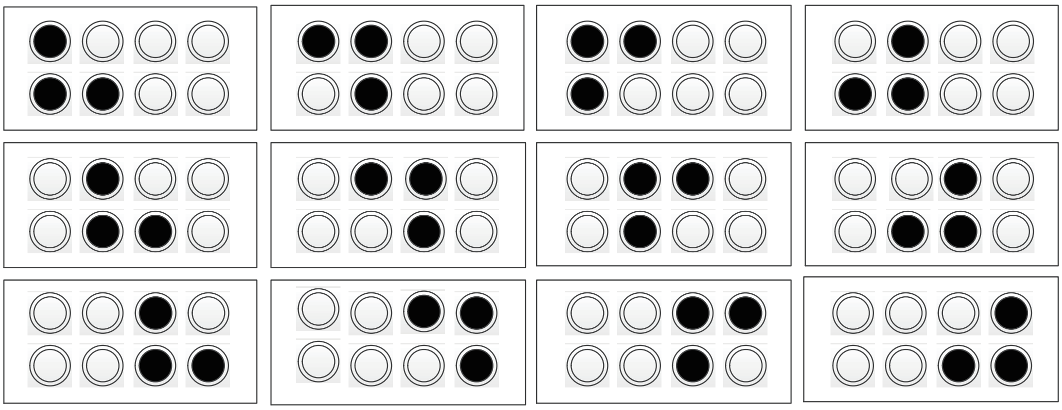

图 3　传统三光束算法光束照明方式

Fig. 3. The manner of illumination for traditional three-beam algorithm.

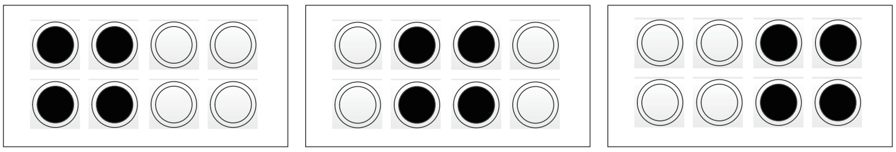

图 4　四光束算法光束照明方式

Fig. 4. The manner of illumination for four-beam algorithm.

一幅高质量图像, 通常需将一系列这样的散斑图像进行平均. 因此, 与传统方法相比, 四光束方法所需的测量次数更少, 数据采集时间更短. 此外, 为进一步克服大气湍流对成像的影响, 传统方法用 12 组三光束的不同组合方法照射目标 (图 3)[11], 本文方法只需三组不同四光束组合发射方式就能达到相同的湍流效应抑制效果 (图 4), 大大减少了光束切换次数, 进一步缩短了数据采集时间, 提高了成像速度.

3　四光束图像复原算法

回波信号数据预处理、波前相位重构和幅值复原是研究算法的三个关键要素. 首先对拍频信号进行预处理, 设置置信区间对信号进行频域滤波, 准确提取主谱线处的散斑相位差和幅值. 运用最小二乘法推导波前相位求解公式并采用高斯赛德尔 (Gauss-Seidel) 松弛法进行迭代求解进而复原波前相位; 利用复原出的波前相位和幅值重构目标图像. 对多幅图像进行平均处理, 可得目标清晰图像.

3.1　波前相位恢复

由 (2) 式的散斑相位差 $\Delta\phi_{01}$ 和 $\Delta\phi_{03}$, 可得波前相位相邻点之间的关系为

$$\begin{cases}\phi(x_i,y_j)=\phi(x_i+s_x,y_j)+\Delta\phi_{01}^{ij},\\ \quad i=1,2,\cdots,K-1, j=1,2,\cdots,M,\\ \phi(x_i,y_j)=\phi(x_i,y_j+s_y)+\Delta\phi_{03}^{ij},\\ \quad i=1,2,\cdots,K, j=1,2,\cdots,M-1.\end{cases}\tag{3}$$

根据最小二乘法[16,17], 将求解 $\phi(x_i,y_j)$ 的问题转化为如下优化问题:

$$\begin{aligned}&\min\sum_{i=1}^{K-1}\sum_{j=1}^{M}[\phi(x_i,y_j)-\phi(x_i+s_x,y_j)-\Delta\phi_{01}^{ij}]^2\\ &+\sum_{i=1}^{K}\sum_{j=1}^{M-1}[\phi(x_i,y_j)-\phi(x_i,y_j+s_y)-\Delta\phi_{03}^{ij}]^2.\end{aligned}\tag{4}$$

求 (4) 式关于 $\phi(x_i,y_j)$ 的偏导数, 并令其等于 0, 整理可得波前相位的求解公式为[18,19]

$$\begin{aligned}&\phi(x_i,y_j)\\ &=\frac{1}{4}[\phi(x_i-s_x,y_j)+\phi(x_i+s_x,y_j)\\ &\quad+\phi(x_i,y_j-s_y)+\phi(x_i,y_j+s_y)-\Delta\phi_{01}^{i-1,j}\\ &\quad+\Delta\phi_{01}^{ij}-\Delta\phi_{03}^{i,j-1}+\Delta\phi_{03}^{ij}],\\ &2\leqslant i\leqslant K-1,\quad 2\leqslant j\leqslant M-1.\end{aligned}\tag{5}$$

同理, 由 $\Delta\phi_{01}$ 和 $\Delta\phi_{12}$ 可得

$$
\begin{aligned}
&\phi(x_i, y_j)\\
&= \frac{1}{4}[\phi(x_i - s_x, y_j) + \phi(x_i + s_x, y_j)\\
&\quad + \phi(x_i, y_j - s_y) + \phi(x_i, y_j + s_y)\\
&\quad - \Delta\phi_{01}^{i,j} + \Delta\phi_{01}^{i+1,j} - \Delta\phi_{12}^{i,j-1} + \Delta\phi_{12}^{i,j}],\\
&2 \leqslant i \leqslant K-1, \quad 2 \leqslant j \leqslant M-1.
\end{aligned}
\tag{6}
$$

由 $\Delta\phi_{12}$ 和 $\Delta\phi_{23}$ 可得

$$
\begin{aligned}
&\phi(x_i, y_j)\\
&= \frac{1}{4}[\phi(x_i - s_x, y_j) + \phi(x_i + s_x, y_j)\\
&\quad + \phi(x_i, y_j - s_y) + \phi(x_i, y_j + s_y)\\
&\quad + \Delta\phi_{23}^{i,j} - \Delta\phi_{23}^{i+1,j} - \Delta\phi_{12}^{i,j} + \Delta\phi_{12}^{i,j+1}],\\
&2 \leqslant i \leqslant K-1, \quad 2 \leqslant j \leqslant M-1.
\end{aligned}
\tag{7}
$$

由 $\Delta\phi_{03}$ 和 $\Delta\phi_{23}$ 可得

$$
\begin{aligned}
&\phi(x_i, y_j)\\
&= \frac{1}{4}[\phi(x_i - s_x, y_j) + \phi(x_i + s_x, y_j)\\
&\quad + \phi(x_i, y_j - s_y) + \phi(x_i, y_j + s_y)\\
&\quad + \Delta\phi_{23}^{i-1,j} - \Delta\phi_{23}^{i,j} - \Delta\phi_{03}^{i,j} + \Delta\phi_{03}^{i,j+1}],\\
&2 \leqslant i \leqslant K-1, 2 \leqslant j \leqslant M-1.
\end{aligned}
\tag{8}
$$

根据 (5)—(8) 式, 利用 Gauss-Seidel 数值计算方法可复原出四幅相位频谱面.

3.2　波前幅值恢复

通过散斑幅值的代数运算可得波前幅值, 令

$$
\begin{aligned}
&\tilde{E}_0 = E_0^2 A_0^2 + E_1^2 A_1^2 + E_2^2 A_2^2 + E_3^2 A_3^2,\\
&\tilde{E}_1 = 2E_0E_1A_0A_1, \quad \tilde{E}_2 = 2E_0E_2A_0A_2,\\
&\tilde{E}_3 = 2E_0E_3A_0A_3, \quad \tilde{E}_4 = 2E_1E_2A_1A_2,\\
&\tilde{E}_5 = 2E_1E_3A_1A_3, \quad \tilde{E}_6 = 2E_2E_3A_2A_3,
\end{aligned}
$$

由此可得波前幅值为

$$
\begin{aligned}
A_0 = \frac{1}{2E_0}\Bigg[&\left(\sum_{i=0}^{6}\tilde{E}_i\right)^{\frac{1}{2}}\\
&+ \left(\tilde{E}_0 - \sum_{i=1}^{3}\tilde{E}_i + \sum_{i=4}^{6}\tilde{E}_i\right)^{\frac{1}{2}}\Bigg].
\end{aligned}
\tag{9}
$$

结合上述求得的 $A_0(x,y)$ 和 $\phi(x,y)$, 通过 (10) 式, 即傅里叶逆变换 [20,21] 可重构四幅目标图像:

$$
\begin{aligned}
g(x', y') = &\iint A_0(u,v)\exp[\mathrm{j}\phi(u,v)]\\
&\times \exp[\mathrm{j}2\pi(ux' + vy')]\,\mathrm{d}u\mathrm{d}v.
\end{aligned}
\tag{10}
$$

上述图像重构算法与传统三光束方法类似, 复杂度并未提高.

4　仿真验证

利用仿真验证四光束成像方法的有效性, 并利用斯特列尔比 (Strehl ratio) 评价重构图像质量, 具体计算公式为 [20]

$$
\begin{aligned}
R_\mathrm{S} = &\left|\iint O_\mathrm{T}(x,y)O_\mathrm{R}(x,y)\mathrm{d}x\mathrm{d}y\right|^2\\
&\times\left[\iint O_\mathrm{T}(x,y)O_\mathrm{T}^*(x,y)\mathrm{d}x\mathrm{d}y\right.\\
&\left.\times\iint O_\mathrm{R}(x,y)O_\mathrm{R}^*(x,y)\mathrm{d}x\mathrm{d}y\right]^{-1},
\end{aligned}
\tag{11}
$$

式中 $O_\mathrm{T}(x,y)$ 为无误差重建图像的强度分布, $O_\mathrm{R}(x,y)$ 为有误差重建图像的强度分布, * 表示共轭. 斯特列尔比越接近 1, 重建图像与目标图像越相似, 图像质量越好.

仿真参数设为: 激光波长 λ 为 532 nm, 采样频率为 4200 Hz, 采样点数为 8400. 四束光之间的频率差分别为 10, 20, 30, 40, 50, 70 Hz, 目标大小为 4 m×4 m, 剪切量 s_x, s_y 均为 0.1 m, 成像距离 R 为 1000 km, 接收阵列维数为 82×82. 频率置信区间设为 8—12 Hz, 18—22 Hz, 28—32 Hz, 38—42 Hz, 48—52 Hz 和 68—72 Hz, 对回波信号进行频域滤波. 利用测量次数、光束切换次数和图像重构算法处理时间衡量成像速度, 对四光束和传统三光束方法的成像效率进行验证.

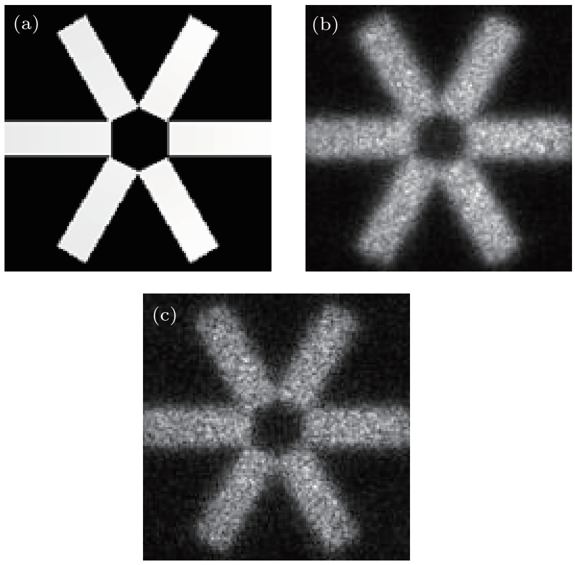

图 5　10 次测量重构图像　(a) 原始图像; (b) 四光束算法; (c) 传统三光束算法

Fig. 5. Reconstructed images via 10 measurements: (a) Original target image; (b) four-beam algorithm; (c) traditional three-beam algorithm.

表 1 四光束与传统算法数据采集次数比较

Table 1. Comparison of data acquisition amount between four-beam and conventional algorithms.

斯特列尔比	0.741	0.789	0.813	0.821	0.829	0.835	0.841	0.844	0.849	0.852	0.854
四光束算法测量次数	1	3	5	7	9	11	13	15	17	19	21
三光束算法测量次数	3	9	13	15	19	22	26	30	35	44	46

1) 测量次数相同时的成像效果

四光束和传统方法10次测量数据平均后的成像结果分别如图5(b)和图5(c)所示, 斯特列尔比分别为0.8348和0.8025. 当测量次数相同时, 四光束算法的重构图像质量比传统算法好, 散斑噪声明显降低.

2) 重构图像斯特列尔比相同时的成像效率

在图像质量相同时, 对四光束与传统算法数据采集次数进行比较, 结果如表1所示. 可以看出, 传统方法的测量次数至少是四光束方法的2—3倍. 因此, 四光束剪切相干成像技术的数据采集速度至少为传统方法的两倍以上. 其中, 斯特列尔比为0.835和0.854的重构图像分别如图6和图7所示.

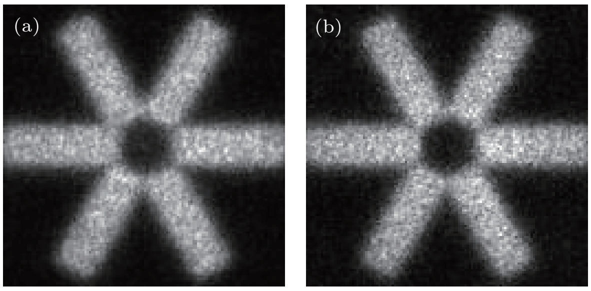

图6 重构图像(斯特列尔比为0.835) (a) 四光束算法; (b) 传统三光束算法

Fig. 6. Reconstructed images (Strehl ratio is 0.835): (a) Four-beam algorithm; (b) traditional three-beam algorithm.

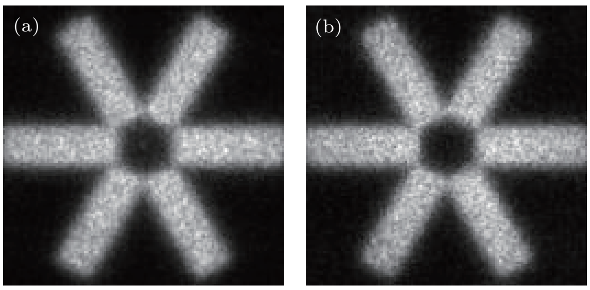

图7 重构图像(斯特列尔比为0.854) (a) 四光束算法; (b) 传统三光束算法

Fig. 7. Reconstructed images (Strehl ratio is 0.854): (a) Four-beam algorithm; (b) traditional three-beam algorithm.

仿真过程中同时对算法处理时间进行统计. 对于单次测量, 传统三光束平均处理时间约为四光束算法的1/2. 根据前述仿真结果, 传统方法的测量次数至少是四光束方法的2—3倍. 综合两方面因素可知, 四光束算法的处理时间不超过传统算法.

此外, 四光束算法还减少了克服大气湍流所需的光束切换次数, 进一步缩短了数据采集时间.

综上, 四光束剪切相干成像技术的成像效率优于三光束方法.

虽然本文方法的硬件成本略高, 比传统方法多了一路小孔径激光发射装置, 但是其数据采集时间却为传统方法的1/2, 成像效率更高, 对远程运动目标的成像识别有显著优势, 便于在短时间内正确反映目标姿态的变化.

5 结　论

本文针对改进的剪切光束成像技术, 进行了成像理论公式推导, 提出了一种四光束剪切相干成像算法. 通过最小二乘法和简单的代数运算, 单次测量能恢复四组波前相位和幅值, 重构四幅目标图像, 减少了成像所需的数据测量次数和光束切换次数. 仿真结果表明, 本文所提方法的数据采集时间比传统方法减少了至少1/2, 成像效率更高, 更适合对远程运动目标的成像识别.

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Target reconstruction algorithm for four-beam sheared coherent imaging

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Abstract

Sheared-beam imaging, which is a nonconventional coherent laser imaging technique, can be used to better solve the problem of taking pictures with high resolution for remote targets through turbulent medium than conventional optical methods. In the previous research on this technique, a target was illuminated by three coherent laser beams that were laterally arranged at the transmitter plane into an L pattern. In order to obtain a high quality image, a series of time-varying scattered signals is collected to reconstruct speckled images of the same object. To overcome atmospheric turbulence, multiple sets of three-beam laser should be emitted, which increases data acquisition time.

In this paper, aiming at the quasi real-time problem of conventional sheared beam imaging technique, we use four-beam laser with rectangular distribution instead of the traditional L type sheared three-beam laser to illuminate the target. According to this, we propose a target reconstruction algorithm for four-beam sheared coherent imaging to reconstruct four target images simultaneously in one measurement, which can acquire high quality images by reducing the amount of measurement and the speckle noise. Meanwhile, it can greatly reduce the amount of beam switching in multi-group emission and improve the imaging efficiency. Firstly, the principle of the four-beam sheared coherent imaging technique is deduced. Secondly, in the algorithm, the speckle amplitude and phase difference frames can be extracted accurately by searching for the accurate positions of the beat frequency components. Based on the speckle phase difference frames, four sets of wavefront phases can be demodulated by the least squares method, and wavefront amplitude can be obtained by algebraic operation of speckle amplitude. The reconstructed wavefront is used for inverse Fourier transform to yield a two-dimensional image. A series of speckled images is averaged to form an incoherent image. Finally, the validity of the proposed technique is verified by simulations. From the simulation results, the image quality of the proposed method is better than that of the traditional method in the same amount of measurement. Furthermore, on the premise of the same image quality, the data acquisition amount of the proposed method is 2-3 times as large as that of the traditional method. In other words, compared with that of the traditional method, the data acquisition time of the proposed method is reduced at least by half and the algorithm processing time is less. It can be concluded that the proposed imaging technique can not only improve the efficiency of target reconstruction, but also present a better way of imaging the remote moving targets.

Keywords: sheared coherent imaging, four-beam, target reconstruction, imaging efficiency

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