光学学报

二值编码相位掩模交替迭代优化的无干涉非相干全息术

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摘要 提出基于交替策略的随机轨迹直接二进制搜索法。数值仿真结果表明，该方法有效抑制了迭代过程中直流偏置的增加并提高迭代速度。实验结果证明，在同样的迭代次数下，该方法显著降低了重建图像的相关重建噪声。该方法推动了无干涉编码孔径相关全息术(I-COACH)系统在可见光范围外成像的应用。

关键词 图像处理；非相干全息术；无干涉编码孔径相关全息术；二值编码相位掩模；直接二进制搜索法

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1 引言

编码孔径相关全息术(COACH)是通过将菲涅耳非相干相关全息术(FINCH)和编码孔径成像(CAI)技术相结合所实现的[1-2]。FINCH系统利用空间光调制器(SLM)将物光分为两束光波，获取其中一束光的自干涉全息图，采用反向传播进行重建。FINCH通过非相干光进行全息成像，使得传统全息术可以不受相干散斑噪声的影响。目前FINCH成功应用于生物医学成像领域[3]，并实现对动态样品的实时快速成像[4]。CAI技术通过对物体的编码和解码重建图像，其中编码是通过将系统的点扩展函数(PSF)与物体进行卷积获得二维编码图像，解码则是通过PSF对二维编码图像进行滤波重建。CAI技术广泛应用于X射线成像[5-6]、压缩感知光谱成像[7-8]、太赫兹雷达成像[9]等多个成像领域。基于FINCH和CAI的原理，Vijayakumar等[2]于2016年提出了COACH系统，在COACH系统中，SLM使用编码相位掩模(CPM)对其中一束进行光调制，通过相移获取自干涉全息图。由于物体上每个点源之间都是不相干的，因此COACH系统获得的全息图实际是物体和PSF的卷积，并通过PSF进行滤波重建。散斑场在衍射过程中会不断发生变化，每个平面都是不一样的随机散斑光场，所以COACH系统记录的物体三维信息不仅编码在光场的相位信息中，还编码在光场的振幅信息中，COACH系统只需要记录不同平面的PSF就能实现三维重建，这使得无干涉COACH(I-COACH)系统可以不通过分波干涉实现非相干三维成像[10-12]，此外I-COACH记录的PSF是正实值函数，需要获取多幅PSF投影到复数域进行重建。最新的无透镜I-COACH(LI-COACH)系统[13-14]不需要使用透镜，使得非相干全息成像系统的结构更为简单。虽然COACH能实现三维重建，但重建图像却有较大的噪声，该噪声主要是点扩展全息图(PSH)频谱不均匀所导致的重建噪声。在算法方面的降噪主要有相位滤波重建(POF)[10]、非线性重建(NLR)[15-17]、LR^{2}A算法[18-19]、压缩感知[20]以及深度学习[21-22]。在这些算法中，通用性好且能有效抑制相关噪声的就是自适应NLR算法，但NLR算法会抑制相关噪声并放大背景噪声，所以直接抑制CPM的重建噪声是十分有必要的。利用不同的CPM记录多个PSF并合成全息图是一种有效降低噪声的方法[23]，对于混沌CPM来说，通过对多幅不相关的PSF进行平均，能有效抑制重建噪声，但使用多幅CPM会降低系统的时间分辨率。为进一步提高COACH系统的重建质量、减少重建所需的CPM，Kumar等[24]提出通过直接搜索法优化二值CPM(bCPM)的方法，将峰值背景比(PBR)作为间接评价PSH重建效果的指标之一[23]，通过直接二进制搜索法(DBSA)优化PSH的PBR，降低重建噪声。DBSA的原理是按顺序依次改变双幅bCPM每个像素点的相位，并计算变化后bCPMs的

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PSH及其PBR，若PBR增加则保留变化，否则恢复原样，直至收敛或达到阈值，同时将CPM二值化能够有效地拓展I-COACH系统的成像光谱范围。然而，在迭代过程中，DBSA虽能实现重建信噪比的提升，但bCPMs的重建效果与PBR并不是呈线性变化。DBSA作为二值全息图的搜索优化算法，仅需对一幅二值掩模进行优化，而I-COACH系统由于需要双幅CPM抑制PSH直流偏置带来的重建噪声，所以DBSA应用于I-COACH系统时需要对双幅bCPM进行迭代。随着DBSA迭代次数的增加，按顺序选择单幅bCPM迭代时，bCPM衍射效率的降低将导致PSH直流偏置的变化，而直流偏置的存在又会严重影响重建图像的质量[25]。此外，DBSA虽然能简单有效地提高全息图质量，但这种变化却是复杂和缓慢的，如何提高DBSA的迭代速度也是需要考虑的问题。

为解决DBSA的稳定性差和迭代速度慢的问题，本文在对I-COACH系统的双幅bCPM进行二进制搜索时，通过交替迭代的策略来确保PSH的直流偏置恒定。又因随机扫描能显著提高DBSA的迭代速度[26-27]，本文采用随机轨迹直接二进制搜索法（DBSRT）扫描bCPM的像素。采用该方法使得DBSA的迭代稳定性和迭代速度得到有效提升，实验结果证明，在对bCPMs仅迭代一轮的情况下，该方法优化的bCPMs具有更低的重建噪声，而且采用bCPM能对可见光范围外的电磁波进行调制，使得I-COACH系统在荧光成像、短波红外成像等方面具有广阔的应用前景。

2　基本原理

2.1　LI-COACH系统原理

LI-COACH光学系统如图1所示，物体平面上的任意位置$\bar{\boldsymbol{r}}_{\mathrm{s}}=\left(x_{\mathrm{s}},y_{\mathrm{s}}\right)$处振幅为$\sqrt{I_{\mathrm{s}}}$的点，在SLM处产生的复振幅为$\sqrt{I_{\mathrm{s}}}\,CL\left(\bar{\boldsymbol{r}}_{\mathrm{s}}/z_{\mathrm{s}}\right)Q\left(1/z_{\mathrm{s}}\right)\exp\left[\mathrm{i}\phi_k(\bar{\boldsymbol{r}})\right]$，其中，$C$为复常数，$\phi_k(\bar{\boldsymbol{r}})$为第$k$个CPM的相位，$z_{\mathrm{s}}$为物体平面到CPM平面的距离，$Q$为二次相位，$Q(a)=\exp\left[\mathrm{i}\pi a\lambda^{-1}\left(x^2+y^2\right)\right]$，$\lambda$为波长，$L$为线性相位，$L(\boldsymbol{r}/z)=\exp\left[\mathrm{i}2\pi\left(r_x x+r_y y\right)/(\lambda z)\right]$。

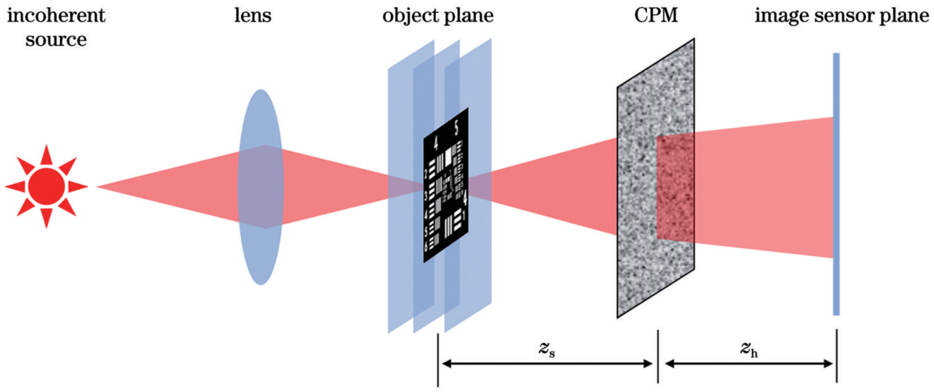

图1　LI-COACH光学结构

Fig. 1　Optical configuration of LI-COACH

最终，在图像传感器平面上的强度分布可以表示为

$$I_k\left(\bar{\boldsymbol{r}}_{\mathrm{h}};\ \bar{\boldsymbol{r}}_{\mathrm{s}},z_{\mathrm{s}}\right)=\left|\sqrt{I_{\mathrm{s}}}\,CQ\left(\frac{1}{z_{\mathrm{s}}}\right)L\left(\frac{\bar{\boldsymbol{r}}_{\mathrm{s}}}{z_{\mathrm{s}}}\right)\exp\left[\mathrm{i}\phi_k(\bar{r})\right]*Q\left(\frac{1}{z_{\mathrm{h}}}\right)\right|^2=I_k\left(\bar{\boldsymbol{r}}_{\mathrm{h}}-\frac{z_{\mathrm{h}}}{z_{\mathrm{s}}}\bar{\boldsymbol{r}}_{\mathrm{s}};\ 0,z_{\mathrm{s}}\right),\tag{1}$$

式中：z_{h}为CPM平面到图像传感器平面的距离；$\bar{\boldsymbol{r}}_{\mathrm{h}}=\left(x_{\mathrm{h}},y_{\mathrm{h}}\right)$为图像传感器平面的坐标；*代表卷积运算符。一个二维物体可视为由M个离散点组成，可将物体表示为

$$O\left(\bar{\boldsymbol{r}}_{\mathrm{s}}\right)=\sum_j^M a_j\delta\left(\bar{\boldsymbol{r}}-\bar{\boldsymbol{r}}_{\mathrm{s},j}\right),\tag{2}$$

式中：$\delta\left(\bar{\boldsymbol{r}}-\bar{\boldsymbol{r}}_{\mathrm{s},j}\right)$为二维物体中的第$j$个点源；$a_j$为二维物体平面上第$j$个点的振幅。

从二维物体发出的光在经过CPM后到达传感器平面。I-COACH作为线性空不变系统，物体在图像传感器平面的光场可以视为物面上每个点源响应的平移叠加。式(1)反映了一个点源的强度响应，而物体可以视作点的集合，因为COACH系统采用非相干光照明，所以物体的强度分布可以视为PSF强度的叠加。物体的强度响应为

$$I_{\mathrm{OBJ}}\left(\bar{\boldsymbol{r}}_{\mathrm{h}};\ z_{\mathrm{s}}\right)=\sum_j a_j I_k\left(\bar{\boldsymbol{r}}_{\mathrm{h}}-\frac{z_{\mathrm{h}}}{z_{\mathrm{s}}}\bar{\boldsymbol{r}}_{\mathrm{s},j};\ 0,z_{\mathrm{s}}\right)。\tag{3}$$

由于图像传感器获得的是正实值图像，两个正实值图像之间进行互相关会产生较大的噪声，这会形成一个不尖锐的相关峰。为抑制直流偏置产生的重建噪声，需要将多幅PSF投影到复数域。合成的PSH可表示为

$$H_{\mathrm{PSH}}\left(\bar{\boldsymbol{r}}_{\mathrm{h}};\ z_{\mathrm{s}}\right)=\sum_{k=1}^K\left[I_k\left(\bar{\boldsymbol{r}}_{\mathrm{h}};\ z_{\mathrm{s}}\right)\exp\left(\mathrm{i}\theta_k\right)\right],\tag{4}$$

式中：K为CPM的总数；$\theta_k=2\pi(k-1)/K$。在I-COACH系统中，单次获得的物体强度响应和PSF均

为正实值随机函数，这使得图像频谱的功率集中在零频信号附近，直流偏置是导致I-COACH系统重建光场时产生噪声的因素之一。因此，在式(4)中参数K至少应为2，而更大的K值能使其更趋近于δ函数。本文中采用$K=2$的情况，有$\exp(\theta_k)=-1$。仅采用双幅CPM的双极PSH可表示为

$$H_{\mathrm{PSH}}(\bar{\boldsymbol{r}}_{\mathrm{h}};\ z_{\mathrm{s}})=I_1(\bar{\boldsymbol{r}}_{\mathrm{h}};\ z_{\mathrm{s}})-I_2(\bar{\boldsymbol{r}}_{\mathrm{h}};\ z_{\mathrm{s}})。\tag{5}$$

在传感器平面的双极物体全息图可表示为

$$H_{\mathrm{OBJ}}(\bar{\boldsymbol{r}}_{\mathrm{h}};\ z_{\mathrm{s}})=I_{\mathrm{OBJ},1}(\bar{\boldsymbol{r}}_{\mathrm{h}};\ z_{\mathrm{s}})-I_{\mathrm{OBJ},2}(\bar{\boldsymbol{r}}_{\mathrm{h}};\ z_{\mathrm{s}})=\sum_j a_j I_{\mathrm{OBJ},1}\left(\bar{\boldsymbol{r}}_{\mathrm{h}}-\frac{z_{\mathrm{h}}}{z_{\mathrm{s}}}\bar{\boldsymbol{r}}_{\mathrm{s},j};\ 0,z_{\mathrm{s}}\right)-\sum_j a_j I_{\mathrm{OBJ},2}\left(\bar{\boldsymbol{r}}_{\mathrm{h}}-\frac{z_{\mathrm{h}}}{z_{\mathrm{s}}}\bar{\boldsymbol{r}}_{\mathrm{s},j};\ 0,z_{\mathrm{s}}\right)=\sum_j a_j H_{\mathrm{PSH}}\left(\bar{\boldsymbol{r}}_{\mathrm{h}}-\frac{z_{\mathrm{h}}}{z_{\mathrm{s}}}\bar{\boldsymbol{r}}_{\mathrm{s},j};\ z_{\mathrm{s}}\right)。\tag{6}$$

通过$H_{\mathrm{OBJ}}(\bar{\boldsymbol{r}}_{\mathrm{h}};\ z_{\mathrm{s}})$与$H_{\mathrm{PSH}}(\bar{\boldsymbol{r}}_{\mathrm{h}};\ z_{\mathrm{s}})$之间的相位滤波进行重建，能进一步去除重建噪声。令$\tilde{H}_{\mathrm{PSH}}(\bar{\boldsymbol{r}}_{\mathrm{h}};\ z_{\mathrm{s}})=\mathcal{F}^{-1}\left\{\exp\left\{\mathrm{i}\cdot\mathrm{angle}\left\{\mathcal{F}\left[H_{\mathrm{PSH}}(\bar{\boldsymbol{r}}_0;\ z_{\mathrm{s}})\right]\right\}\right\}\right\}$，$\mathcal{F}(\cdot)$代表傅里叶变换，$\mathcal{F}^{-1}(\cdot)$代表傅里叶逆变换，angle$(\cdot)$代表求相位，物体全息图的POF重建结果为

$$R(\bar{\boldsymbol{r}}_{\mathrm{R}})=H_{\mathrm{OBJ}}(\bar{\boldsymbol{r}}_{\mathrm{h}};\ z_{\mathrm{s}})\otimes\tilde{H}_{\mathrm{PSH}}(\bar{\boldsymbol{r}}_{\mathrm{h}}-\bar{\boldsymbol{r}}_{\mathrm{R}};\ z_{\mathrm{s}})=\iint\sum_j\left[a_j H_{\mathrm{PSH}}\left(\bar{\boldsymbol{r}}_{\mathrm{h}}-\frac{z_{\mathrm{h}}}{z_{\mathrm{s}}}\bar{\boldsymbol{r}}_{\mathrm{s},j};\ z_{\mathrm{s}}\right)\tilde{H}^{*}_{\mathrm{PSH}}(\bar{\boldsymbol{r}}_{\mathrm{h}}-\bar{\boldsymbol{r}}_{\mathrm{R}};\ z_{\mathrm{s}})\right]\mathrm{d}\bar{\boldsymbol{r}}_{\mathrm{h}}=\sum_j\left[a_j\iint H_{\mathrm{PSH}}\left(\bar{\boldsymbol{r}}_{\mathrm{h}}-\frac{z_{\mathrm{h}}}{z_{\mathrm{s}}}\bar{\boldsymbol{r}}_{\mathrm{s},j};\ z_{\mathrm{s}}\right)\tilde{H}^{*}_{\mathrm{PSH}}(\bar{\boldsymbol{r}}_{\mathrm{h}}-\bar{\boldsymbol{r}}_{\mathrm{R}};\ z_{\mathrm{s}})\mathrm{d}\bar{\boldsymbol{r}}_{\mathrm{h}}\right]=\sum_j\left[O\left(\frac{\bar{\boldsymbol{r}}_{\mathrm{s}}}{M_{\mathrm{T}}}\right)\Lambda\left(\bar{\boldsymbol{r}}_{\mathrm{R}}-\frac{z_{\mathrm{h}}}{z_{\mathrm{s}}}\bar{\boldsymbol{r}}_{\mathrm{s},j}\right)\right]\approx O\left(\frac{\bar{\boldsymbol{r}}_{\mathrm{s}}}{M_{\mathrm{T}}}\right),\tag{7}$$

式中：$\otimes$表示互相关运算；$\Lambda(\cdot)$为类δ函数；$M_{\mathrm{T}}=z_{\mathrm{h}}/z_{\mathrm{s}}$为成像系统的横向放大率。采用POF对PSH进行自相关重建的结果为

$$P(\bar{\boldsymbol{r}}_{\mathrm{R}})=H_{\mathrm{PSH}}(\bar{\boldsymbol{r}}_{\mathrm{h}};\ z_{\mathrm{s}})\otimes\tilde{H}_{\mathrm{PSH}}(\bar{\boldsymbol{r}}_{\mathrm{h}}-\bar{\boldsymbol{r}}_{\mathrm{R}};\ z_{\mathrm{s}})=\iint H_{\mathrm{PSH}}(\bar{\boldsymbol{r}}_{\mathrm{h}};\ z_{\mathrm{s}})\tilde{H}^{*}_{\mathrm{PSH}}(\bar{\boldsymbol{r}}_{\mathrm{h}}-\bar{\boldsymbol{r}}_{\mathrm{R}};\ z_{\mathrm{s}})\mathrm{d}\bar{\boldsymbol{r}}_{\mathrm{h}}=\Lambda(\bar{\boldsymbol{r}}_{\mathrm{R}})。\tag{8}$$

2.2　随机轨迹DBSA原理

基于菲涅耳衍射的Gerchberg-Saxton(G-S)算法生成bCPM的流程如图2所示，图中ϕ_{rand}为纯随机相位，ϕ_k为第k个CPM的相位。首先对G-S算法生成的双幅CPM进行二值化，二值化结果作为DBSA迭代的初始bCPM。将G-S算法生成的CPM加入二次相位$Q(-1/z_{\mathrm{s}})$后进行二值化，使$-\pi\sim0$的相位变为$-\pi/2$，$0\sim\pi$的相位变为$\pi/2$，通过G-S算法生成两幅独立的bCPM，将其作为DBSA的输入初始值。

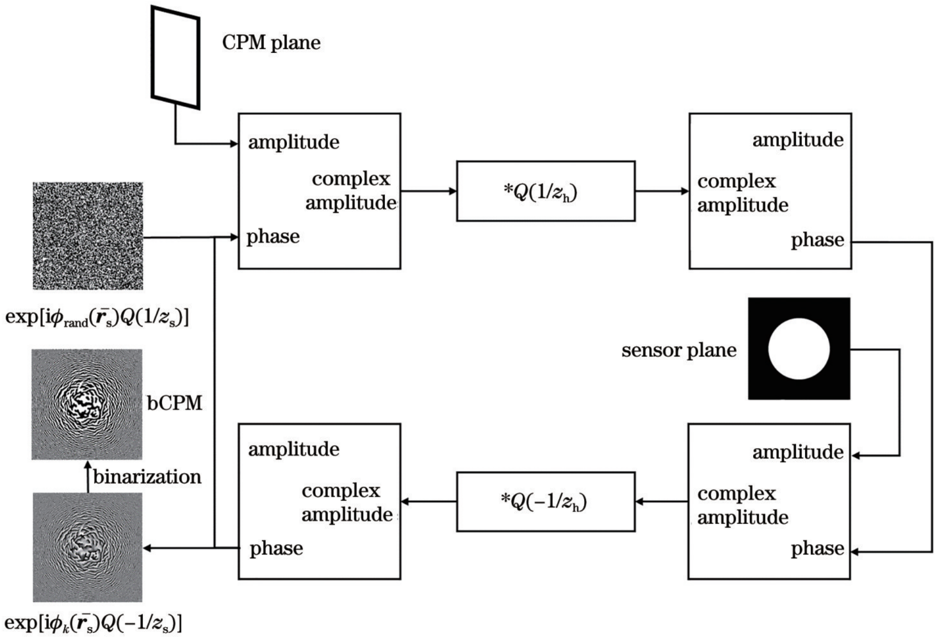

图2　G-S算法生成bCPM

Fig. 2　G-S algorithm generates bCPM

一般来说，DBSA的评价指标为计算全息图再现像的归一化标准差。由于COACH系统通过CPM进行相关重建，因此描述CPM重建质量的一个重要指标是PBR[23]，PBR描述的是PSH自相关信号$P(\bar{\boldsymbol{r}}_{\mathrm{R}})$的峰值信号与背景信号功率之比，而重建图像为目标物与$P(\bar{\boldsymbol{r}}_{\mathrm{R}})$的卷积。PBR的表达式为

$$R_{\mathrm{PB}}(n)=\frac{M^{2}\left|P_{n}\left[\bar{\boldsymbol{r}}_{\mathrm{R}}=(0,0)\right]\right|}{\sum_{x,y=-M/2}^{x,y=M/2}\left|P_{n}(\bar{\boldsymbol{r}}_{\mathrm{R}})\right|},\tag{9}$$

式中：n为DBSA的迭代次数。为提高DBSA的迭代速度和迭代稳定性，采用DBSRT对双幅bCPM进行交替迭代，双幅像素为M pixel×M pixel的bCPM所需迭代次数$N=2M^2$。在第n次迭代时，若n为奇数则选择bCPM1迭代，若n为偶数则选择bCPM2迭代，接着随机选取该bCPM上未被扫描过的像素点，并将该像素点进行翻转，若该像素点的相位为$\pi/2$则翻转为$-\pi/2$，反之$-\pi/2$翻转为$\pi/2$，然后获得bCPM1和bCPM2的PSH，若该像素点翻转后PBR提升，则保留像素翻转后的bCPM，反之则复原，直至对双幅bCPM上的全部像素点扫描完。直接搜索法虽能缓慢提高全息图的PBR，但随着迭代次数的增加，bCPM的衍射效率将产生一定的下降。

为抑制全息图的直流偏置，DBSA至少需要对双幅bCPM进行迭代，而原本的DBSA采用字典顺序进行扫描，且对其中一幅bCPM迭代完后才会对另一幅bCPM进行迭代，这种方法使双幅bCPM的变化并不趋同，从而导致PSH直流偏置发生变化。由于双幅及以上CPM合成的H_{PSH}并非全是正实值，因此其自相关函数($H_{\mathrm{PSH}}\otimes H_{\mathrm{PSH}}$)实际上是存在负值的，若伪随机函数PSH的直流偏置接近于零，此时PSH除自相关峰外的区域平均值也趋近于零。由式(7)和式(8)可知，物体的重建结果等于物体与PSH自重建信号的卷积，而PSH的直流偏置将使得P_n背景区噪声信号的平均值并不为零，进而影响系统的重建结果。本文选择P_n背景区的直流偏置值来评价PSH的直流偏置，这使得直流偏置对相关重建效果的评价更准确。

I-COACH系统作为一种衍射受限系统，分辨率受到SLM的面积和散射度的影响，而针孔大小也对$P(\bar{\boldsymbol{r}}_{\mathrm{R}})$产生影响，所以$P(\bar{\boldsymbol{r}}_{\mathrm{R}})$并非严格的$\delta$函数，而是和系统重建效果相关的类$\delta$函数，中间的主峰决定了系统的分辨率，除主峰区域外的信号均为背景噪声信号。为表征PSH自相关重建的背景直流偏置，将这个类δ函数主峰以外的区域作为背景区域，并除以R_{PSH}的峰值信号值，此时背景信号的直流偏置为

$$B(n)=\frac{1}{S_{\mathrm{b}}}\left|\sum_{j}^{A_{\mathrm{b}}}\frac{P_{n}(\bar{\boldsymbol{r}}_{\mathrm{R},j})}{P_{n}\left[\bar{\boldsymbol{r}}_{\mathrm{R}}=(0,0)\right]}\right|,\tag{10}$$

式中：S_{b}为背景区域面积；A_{b}为背景区域；$\bar{\boldsymbol{r}}_{\mathrm{R},j}$为$\bar{\boldsymbol{r}}_{\mathrm{R}}$坐标平面上第$j$个点的坐标。

3 基于DBSA的迭代优化仿真计算

3.1 初始条件的确定

对LI-COACH系统进行仿真，模拟物面上的点源经过CPM在像面生成的PSF，并计算PBR、直流偏置的变化。波长$\lambda=532$ nm，CPM的像素总数为500×500，像素大小为6.3 μm×6.3 μm，物距为225 mm，像距为180 mm，以USAF1951分辨率板的4、5、6、7组的元素作为目标物，计算迭代过程中重建图像的PSNR。

3.2 基于DBSA对bCPM的迭代优化

在图2 G-S算法中，在传感器平面约束函数的面积越大则散射度越大，散射度过大会使得PSH的强度较低，从而增加背景噪声，仿真中散斑的约束形状约为直径2 mm的圆形。将G-S算法获得双幅不同的bCPM作为初始掩模，利用两种搜索法对bCPM进行迭代优化，迭代过程中重建图像PSNR和背景直流偏置与迭代次数的关系如图3所示。图3(a)为DBSA顺序选择bCPM迭代，明显可见两个变量具有负相关性，而且背景直流偏置的增加使得重建图像PSNR严重降低，特别是在第一幅bCPM优化完成时，即25万次的迭代时的重建效果最差，此时P_n的背景直流偏置最大，相反，在背景直流偏置最小的情况下，其重建质量最好。同时可以注意到，在第二幅bCPM优化完成时，

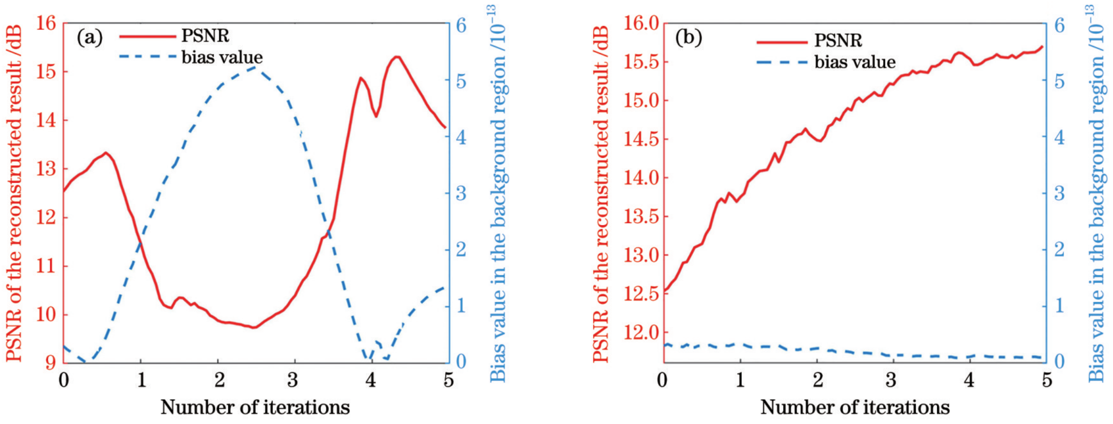

图3 PSNR和直流偏置与迭代次数的关系图。(a) DBSA顺序选择bCPM迭代；(b) DBSRT交替选择bCPM迭代

Fig. 3 Plots of PSNR and the DC bias value versus the number of iterations. (a) DBSA sequentially selects bCPM iterations; (b) DBSRT alternately selects bCPM iterations

背景直流偏置并没有归零。图3(b)为DBSRT采用交替选择bCPM迭代的结果，可见采用交替选择bCPM的策略能有效抑制背景直流偏置。

3组bCPMs对目标物进行POF重建的图像如图4所示。其中，图4(a)为初始bCPMs对物体的重建图像，图4(b)为经DBSA优化的bCPMs对物体的重建图像，图4(c)为DBSRT交替策略优化后的bCPMs对物体的重建图像。可见，在仅对bCPMs的每个像素扫描一次的情况下，DBSA虽然能改善初始bCPMs的重建效果，但效果却不如基于交替策略的DBSRT。

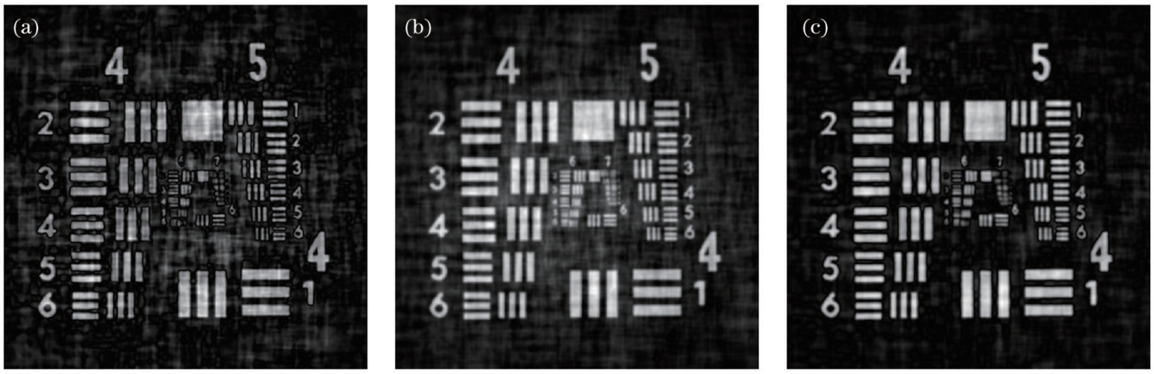

图4 bCPMs重建图像。(a)初始bCPMs重建图像；(b) DBSA优化后的重建图像；(c) DBSRT交替策略优化后的重建图像

Fig. 4 Reconstructed images of bCPMs. (a) Reconstructed image by initial bCPMs; (b) reconstructed image after DBSA; (c) reconstructed image after DBSRT for alternating strategies

若仅对bCPM1进行迭代，DBSA和DBSRT在迭代过程中，PBR的变化与迭代次数的关系如图5所示，可见，随机轨迹扫描使得直接搜索法的迭代速度提高一倍左右。

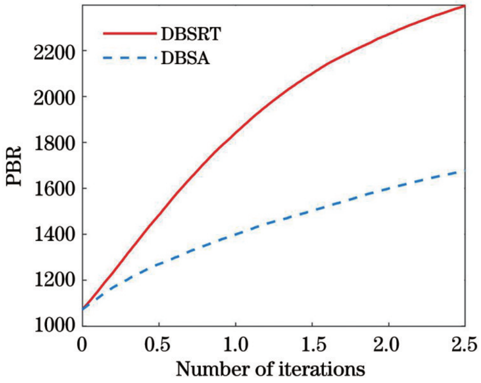

图5 PBR与迭代次数的关系图

Fig. 5 PBR varying with the number of iterations

4 二值CPM重建效果的实验验证与评价

图6为LI-COACH实验系统，通过在物体平面放置针孔和目标物，分别记录系统的PSF和物体的强度响应。记录物体信息的非相干光源为准单色发光二极管(LED)(λ=532 nm)，系统采用临界照明的方式，并利用直径为25 μm的针孔模拟理想点源。物体和针孔发出的光束，经过偏振片后偏振方向与SLM的调制方向相同，将bCPM1和bCPM2依次加载于SLM(相位调制，1280×1280分辨率，6.3 μm像素间距)上，并使用CMOS图像传感器(上海大恒光学精密机械有限公司，单色，1280×1024分辨率，5.2 μm像素间距)记录相应的PSF。实验装置中针孔和物体的平面到SLM的距离为225 mm，SLM到CMOS的距离为180 mm。

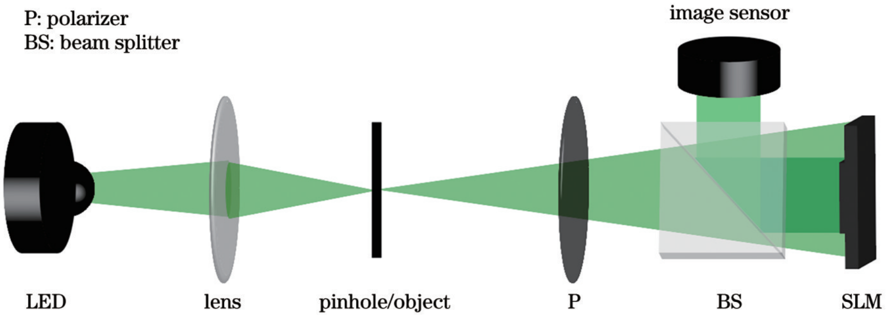

图6 LI-COACH实验装置图

Fig. 6 Experimental setup of LI-COACH

选择USAF1951分辨率板的1组2号元素作为目标物，实验结果如图7所示。图7(a1)、(b1)分别为G-S算法生成的初始bCPM1和初始bCPM2，图7(a2)～(a5)为优化前后bCPM1生成的PSF和物体

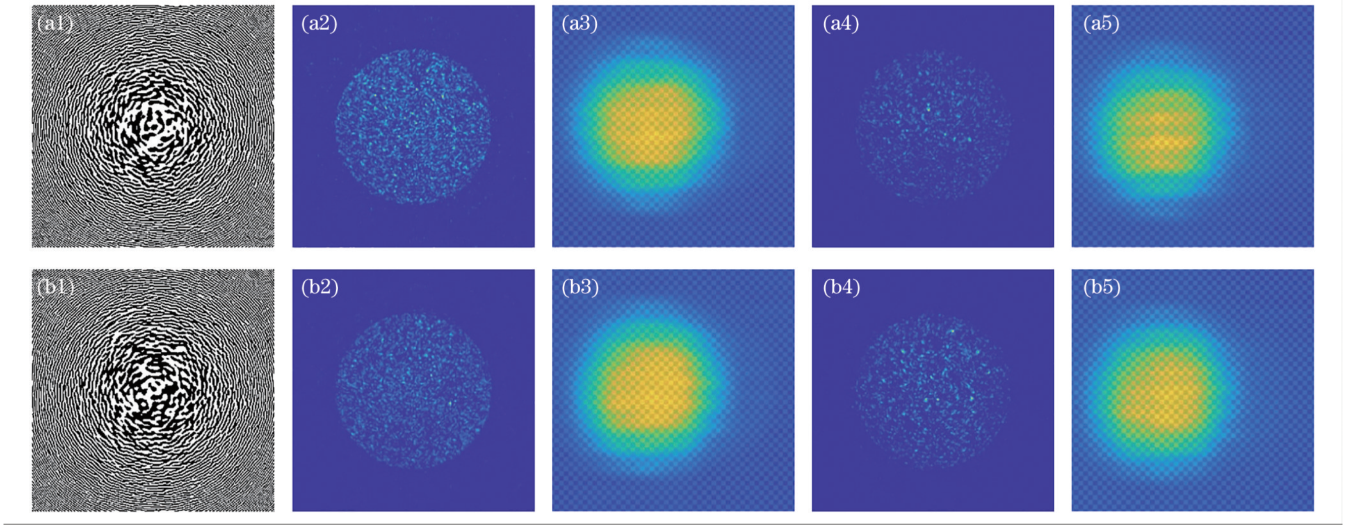

图7　实验数据。(a1)(b1)二值 CPM：bCPM1 和 bCPM2；(a2)(b2)初始 bCPM 的 PSF；(a3)(b3)初始 bCPM 的物体强度响应；(a4)(b4)优化后bCPM 的 PSF；(a5)(b5)优化后bCPM 的物体强度响应

Fig. 7　Experimental data. (a1)(b1) Binary CPMs: bCPM1 and bCPM2; (a2)(b2) PSF of initial bCPM; (a3)(b3) object intensity response of initial bCPM; (a4)(b4) PSF of optimized bCPM; (a5)(b5) object intensity response of optimized bCPM

强度响应，图 7(b2)～(b5)为优化前后 bCPM2 生成的 PSF 和物体的强度响应。可见，bCPM 经优化后生成的 PSF 有较大变化。为评价 bCPMs 的 PSF 重建效果，通过分析 PSH 的参数来间接评价其重建效果，其中初始 bCPMs的 PSH PBR 为 767.0，采用 DBSA 优化的 bCPMs的 PSH PBR 为 858.5，可见 DBSA 能有效提高 PBR。

将获得的实验数据合成 PSH 和物体全息图，并采用 POF 进行重建，结果如图 8 所示。其中，图 8(a)为双极 PSH，图 8(b)为双极物体全息图，图 8(d)为通过在 SLM 上加载透镜相位得到的常规成像结果。对不同 bCPMs 的重建图像进行分析，图 8(c)为初始 bCPMs 的重建图像(PSNR 为 15.6 dB)，图 8(e)为 DBSA 按顺序迭代优化的 bCPMs 重建图像(PSNR 为 17.5 dB)，图 8(f)为该方法优化的 bCPMs 重建图像(PSNR 为 19.5 dB)。可见，该方法具有更好的重建效果。图 8(g)为选择 DBSA 优化的 bCPM1 和未优化的 bCPM2 进行重建的结果，此时重建图像 PSNR 为 9.6 dB，可见 DBSA 按顺序迭代需要完成 bCPM1 和 bCPM2 的迭代后才能有效降低重建噪声。

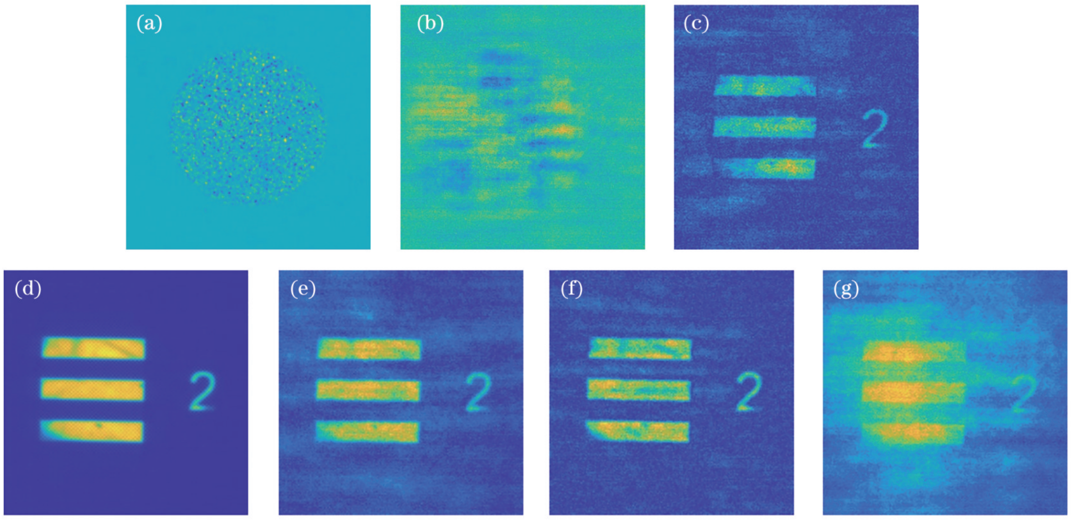

图8　实验重建图像。(a) PSH；(b)物体全息图；(c)初始 bCPMs 重建图像；(d)常规成像；(e) DBSA 优化后的重建图像；(f) DBSRT 交替策略优化后的重建图像；(g) DBSA 优化的 bCPM1 和初始 bCPM2 的重建图像

Fig. 8　Experimental reconstruction images. (a) PSH; (b) hologram of the object; (c) initial bCPMs reconstruction image; (d) regular image; (e) reconstructed image after DBSA optimization; (f) reconstructed image after DBSRT for alternating strategies; (g) reconstruction image of bCPM1 optimized by DBSA and initial bCPM2

5 结论

本文提出采用交替策略DBSRT对bCPMs进行迭代优化的方法，该方法具有迭代的稳定性更好以及速度更快的优点。理论分析和数值仿真结果表明，在DBSA迭代过程中直流偏置的变化是影响优化效果的重要因素之一，通过交替策略进行迭代能有效约束PSH的直流偏置，采用随机轨迹扫描可显著提高DBSA的迭代速度。该方法使得DBSA的稳定性和速度有了明显提升，在同样的迭代次数下能进一步提高系统的重建效果。采用交替策略DBSRT能够有效减少DBSA的迭代次数，提高系统的重建质量，为基于bCPM的I-COACH系统的快速、高质量重建提供了一种简单有效的方法。

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Interferenceless Incoherent Holography Optimized by Alternate Iteration of Binary Coded Phase Mask

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Abstract

Objective Interferenceless coded aperture correlation holography (I-COACH) employs incoherent illumination, distinct from other coherent holography techniques. In I-COACH, phase information is redundant, and only the intensity pattern of the three-dimensional observation scene is required to recover object information. Owing to its interference-free nature, it offers the advantages of a simpler optical path and more convenient processing, transmission, and storage of data. This has led to the development of an even more simplified, lensless I-COACH (LI-COACH) system. Utilizing a coded phase mask (CPM), the object intensity is encoded into a specific speckle pattern. The object's speckle hologram and the corresponding point spread hologram (PSH) are used for object reconstruction through cross-correlation, but this reconstruction method is associated with considerable background noise. I-COACH system based on binary coded phase mask significantly reduces reconstruction noise while expanding the imaging spectral range. In this approach, the peak-to-background ratio of the PSH is enhanced using a direct binary search method to reduce the system's reconstruction noise. However, this method increases the bias value of the PSH during the iteration process, leading to unstable iteration effects, and the use of dictionary order scanning results in slower iteration speeds. This paper proposes a direct binary search method based on an alternate strategy with random trajectories. Numerical simulations demonstrate that this method effectively suppresses the increase in the bias value during the iteration process and enhances the iteration speed. Experimental results confirm that, with the same number of iterations, this method significantly reduces the correlation reconstruction noise. This method advances the application of the I-COACH system in imaging beyond the visible light range, offering broad application prospects in fields such as astronomy and the military.

Methods Our design is based on the principle of DBSA and employs a variant known as binary search with random trajectory (DBSRT) to alternately iterate two binary coded phase masks (bCPMs). Initially, two independent CPMs are generated using the Gerchberg-Saxton (G-S) algorithm, which are then binarized to serve as the initial values for the DBSA. The peak-to-background ratio (PBR) is used as an indirect metric to evaluate the reconstruction effect of the PSH, and the DBSRT is utilized to optimize the PBR of the PSH to reduce reconstruction noise. To ensure the bias value is a constant during the iteration process, the improved DBSA selects bCPM1 for iteration when the number of iterations is odd, and bCPM2 when it is even. To further increase the iteration speed, a random unscanned pixel on the bCPM is selected, and its phase is inverted. The PSH and its PBR of the altered bCPMs are calculated in the meantime. If the PBR increases, the change is retained; otherwise, it is reverted to its original state. This process is continued until convergence is reached or a threshold is met. Finally, the iterated bCPMs are used as the random phase masks in the I-COACH system.

Results and Discussions In the experiment, Element 2 of Group 1 from the USAF1951 resolution test chart is chosen as the target. Significant changes are observed in the PSH and object intensity response generated by both the initial bCPMs and those optimized using DBSA (Fig. 8). The experimental data is synthesized into PSH and object holograms, followed by reconstruction using POF. This method demonstrates a substantial improvement in imaging quality compared to the original method (Fig. 8). The images reconstructed from the initial bCPMs and the original DBSA-optimized bCPMs have PSNRs of 15.6 dB and 17.5 dB respectively, while the image from the bCPMs optimized by our method has a PSNR of 19.5 dB, indicating a better reconstruction effect. However, the reconstruction of the target object from bCPMs optimized by DBSA for only bCPM1 yielded a PSNR of 9.6 dB. This shows that sequential iteration by DBSA needs to complete iterations of both bCPM1 and bCPM2 to effectively reduce reconstruction noise. This is attributed to the variation in the bias value of the PSH when only one of the bCPMs is iterated, with the bias value being a contributing factor to noise in the reconstructed light field of the I-COACH system.

Conclusions We propose an alternating strategy for iteratively optimizing bCPMs, which offers improved stability and increased speed in iterations. Through theoretical analysis and numerical simulations, it has been demonstrated that changes in the bias value during DBSA iterations are one of the crucial factors affecting the optimization results. Iterating with an alternating strategy effectively constrains the bias value of the PSH and employing random trajectory scanning significantly enhances the iteration speed of DBSA. This method has notably improved the stability and speed of DBSA. Experimental results show that this approach further enhances the system's reconstruction performance with the same number of iterations. The alternating strategy in DBSRT effectively reduces the number of iterations required by DBSA, thereby improving the reconstruction quality of the system. This provides a straightforward and effective method for fast, high-quality reconstruction in I-COACH systems based on bCPM.

Key words image processing; incoherent holography; interferenceless coded aperture correlation holography; binary coded phase masks; direct binary search algorithm