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Low-photon counts Coherent Modulation Imaging via Generalized Alternating Projection Algorithm

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INTRODUCTION

Phase contrast imaging is advantageous for mitigating radiation damage to samples, such as biological specimens. For imaging at nanometer or atomic resolution, the required flux on samples increases dramatically and can easily exceed the sample damage threshold. Coherent modulation imaging (CMI) can provide quantitative absorption and phase images of samples at diffraction-limited resolution with fast convergence.

When used for radiation-sensitive samples, CMI experiments need to be conducted under low illumination flux for high resolution.

Here, an algorithmic framework is proposed for CMI involving generalized alternating projection and total variation constraint. A five-to-ten-fold lower photon requirement can be achieved for near-field or far-field experiment dataset.

METHODS

Generally, phase retrieval is a non-convex optimization problem, due to the intensity measurement of wavefields.

Unlike convex situations, non-convex optimization problems are at risk of stagnation at local minima and saddle points.

Current phase retrieval algorithms usually introduce additional regularizing priors to the optimization function to reduce the scope of the solution space. In the following, we briefly sketch the basics of the proposed CMI-GAP algorithm.

Objective function:

$$prox_g(x,\lambda) = \arg\min_x \|Ax-y\|_2^2 + \lambda g(x) \quad (1)$$

Under GAP framework:

$$(x,z) = \arg\min \frac{1}{2}\|y-Ax\|_2^2 + \lambda g(z) \;\; s.t. \;\; x=z \quad (2)$$

Reformulated as:

$$(x,z) = \arg\min \frac{1}{2}\|y-Ax\|_2^2 + \|x-z\|_2^2 + \lambda g(z) \quad (3)$$

Updating x, given z:

$$x = \arg\min \frac{1}{2}\|y-Ax\|_2^2 + \|x-z\|_2^2 \quad (5)$$

$$x^{k+1} = z^k + A^T\left(AA^T\right)^{-1}\left(y-Az^k\right) \quad (6)$$

Updating z: given x :

$$z = \arg\min \|x-z\|_2^2 + \lambda \|z\|_{TV} \quad (7)$$

$$z^{k+1} = TV\left(x^{k+1}\right) \quad (8)$$

Figure 1 consists of two parts, forward propagation via CMI and inverse propagation via GAP.

The introduction of TV regularization helps improve the performance under low lighting conditions.

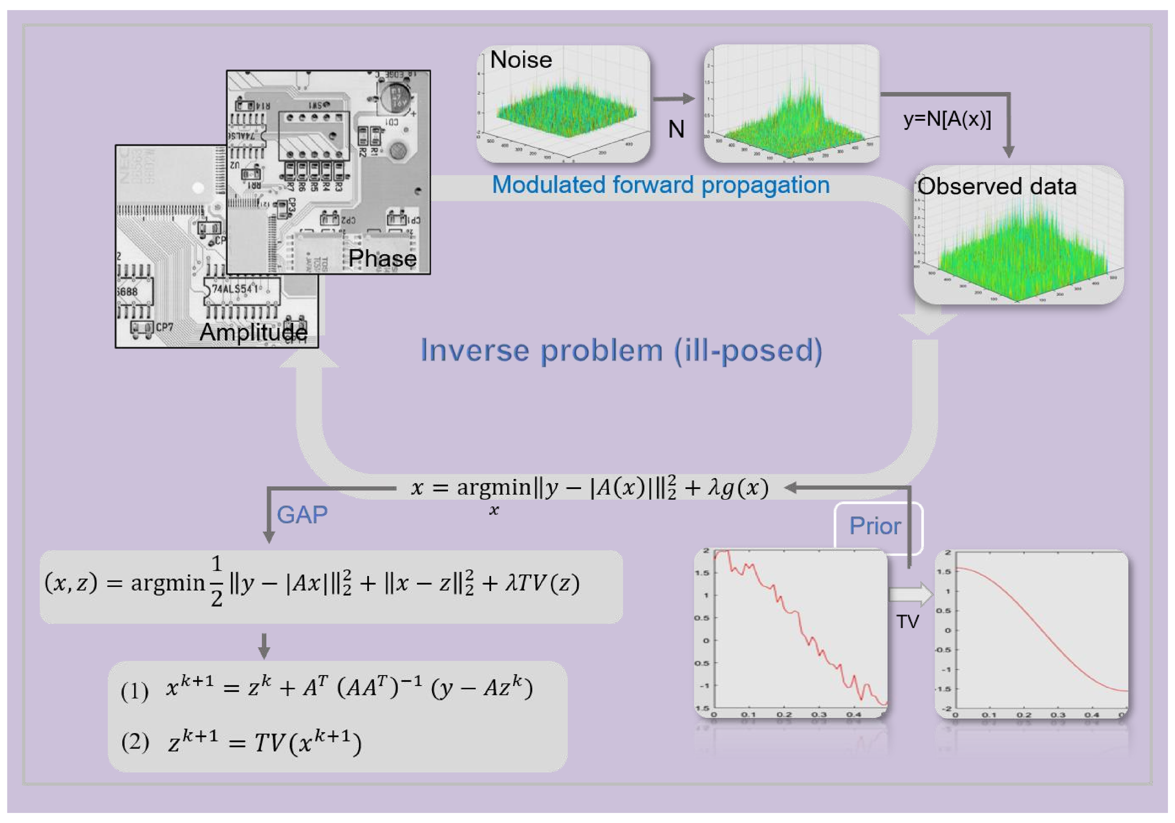

Fig. 1 Flowchart of the proposed CMI-GAP algorithm.

RESULTS

Near-field simulations & Parameters:

- Total illumination photon number: $10^7/10^8$
- Distance (sample-modulator): 22.1 mm
- Distance (modulator-detector): 21.5mm
- Wave propagation: Angular spectrum
- Sampling intervals: 5.04mm
- Wavelength: 632.8nm

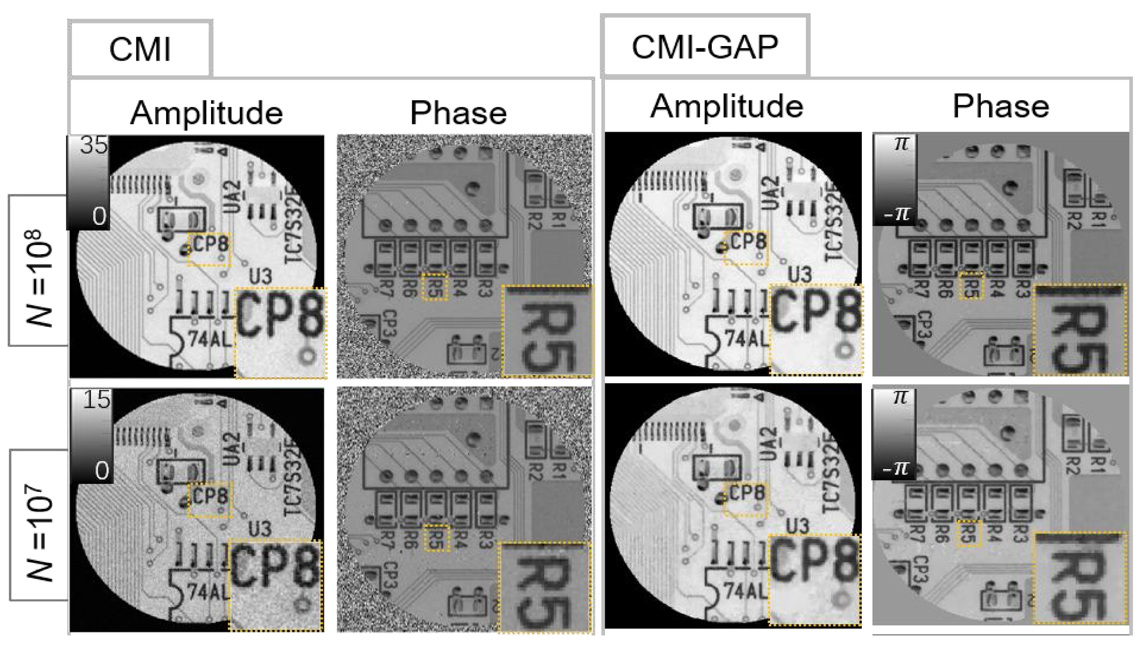

Fig.2 Reconstruction of the sample given near-field CMI simulated data.

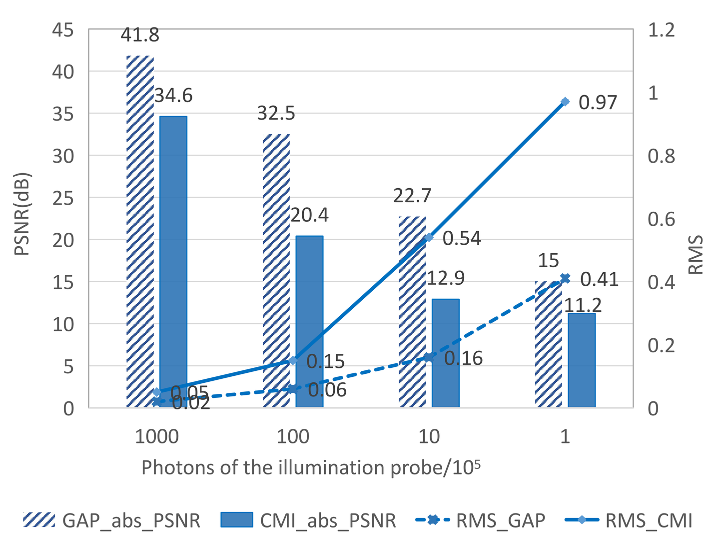

Fig.3 Error metrics comparison

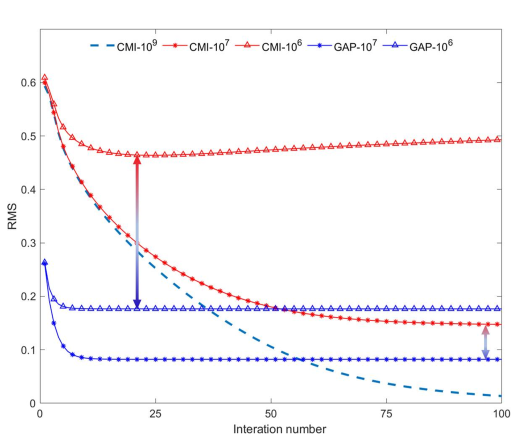

Fig.4 Convergence curve

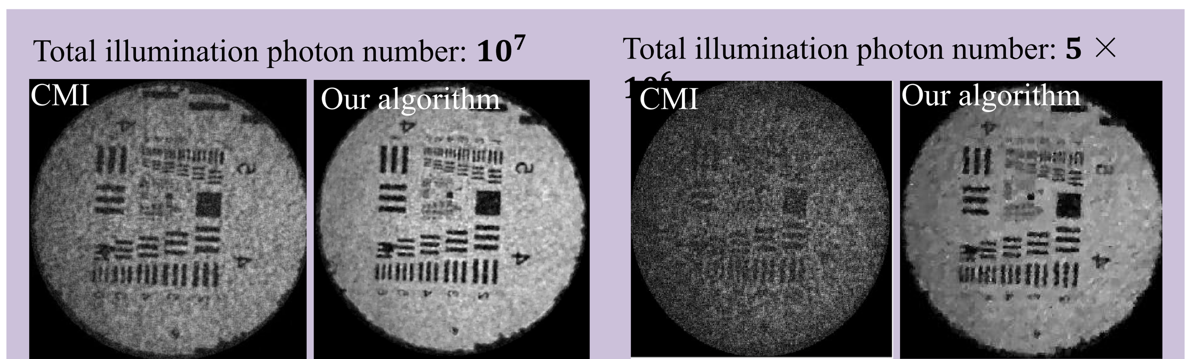

Fig.5 Near-field experiments (Only amplitudes)

Number of photons	10^7	5×10^6
RMS of CMI-GAP	0.31	0.45
RMS of CMI	0.50	0.76

Table 1. RMS corresponding to the near-field CMI.

Far-field simulations & Parameters:

- Total illumination photon number: $10^7/10^8$
- Distance (sample-modulator): 30.8 mm
- Distance (modulator-detector): 30mm
- Sampling intervals: 5.04mm
- Wavelength: 632.8nm

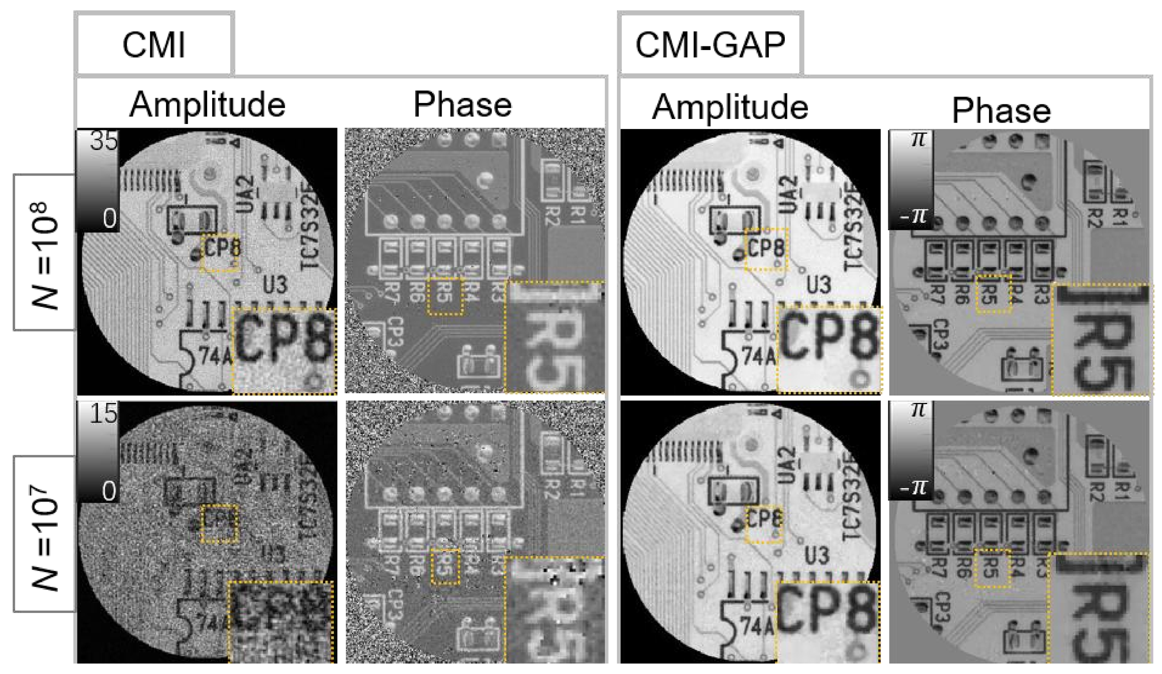

Fig.6 Reconstruction of the sample given far-field CMI simulated data

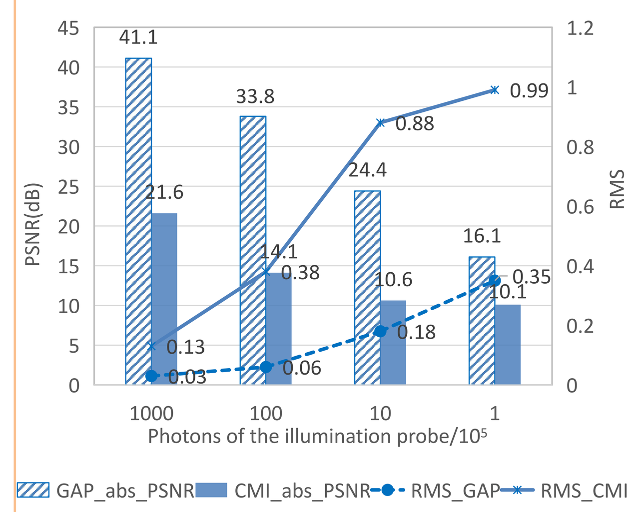

Fig.7 Error metrics comparison

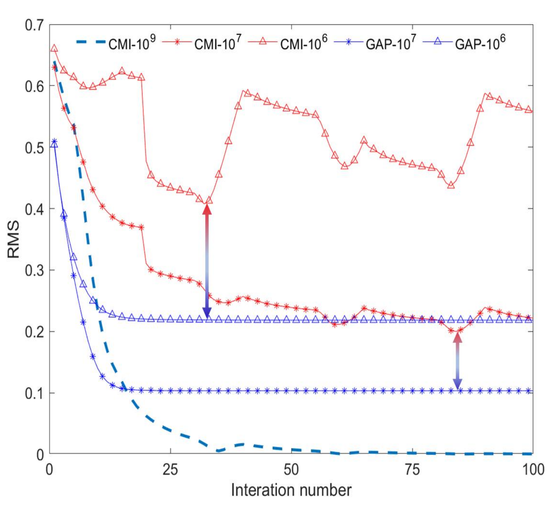

Fig.8 Convergence curve

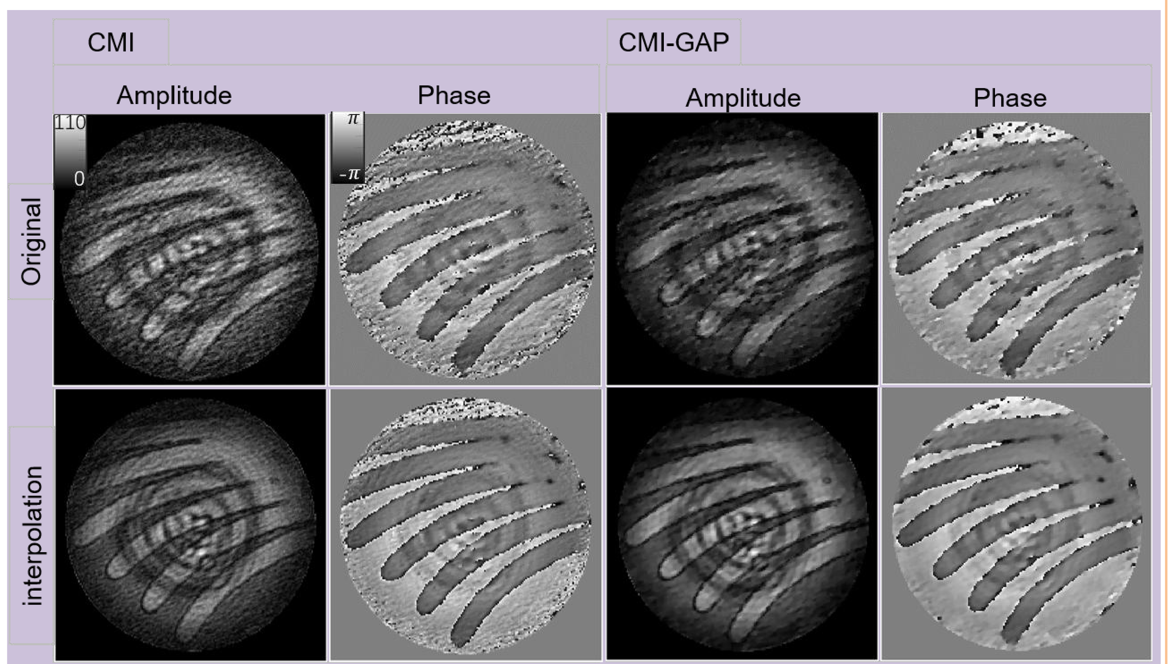

Fig.9 Reconstruction of the far-field CMI experimental data. Top-right: Reconstructions with proposed algorithm. Bottom-left: Reconstructions of original algorithm with 2 × 2 subdivision. Bottom-right: Reconstructions of proposed algorithm with 2 × 2 subdivision.

CONCLUSIONS

These results demonstrate our method outperforms the current CMI algorithm in convergence and image quality when the flux of illumination is lower than 10^7. When the number of photons reduces below 10^6, CMI failed completely while some sample features could still be retrieved with the CMI-GAP algorithm. CMI-GAP is robust to noise with enhancement as much as 20dB on PSNR and three times on RMS.

The work would make CMI more applicable to the dynamics study of radiation-sensitive samples.

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