PHASE RETRIEVAL MICROSCOPE USING PHOTON IMAGING DETECTOR

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Phase retrieval was achieved with higher accuracy than ever from the Fraunhofer diffraction pattern that was measured with a photon imaging detector up to higher diffraction orders.

1. Introduction

Iterative algorithms for phase retrieval have been studied numerically and experimentally for more than two decades.[1] The phase distribution $\phi(\boldsymbol{u})$ of a transparent object can be recovered from the Fraunhofer diffraction pattern $|F(\boldsymbol{u})|^2$, where $F(\boldsymbol{u})$ is the Fourier transform of the amplitude transmittance of the object $f(\boldsymbol{u})$. Each loop of the Fourier iterative algorithm mainly consists of four steps as described in Fig.1,: **1)** $f(\boldsymbol{u})$ is Fourier transformed, **2)** the Fourier domain constraint including $|F(\boldsymbol{u})|$ is imposed on, **3)** $F(\boldsymbol{u})$ is inverse Fourier transformed, **4)** the object domain constraint is imposed on, and these procedures are iterated until the algorithm converges. It has been numerically demonstrated that the accuracy of the retrieved distribution is affected by the dynamic range of $|F(\boldsymbol{u})|^2$.[2] The retrieved phase distribution may be unstable in the presence of small noise perturbations in measurement. The diffraction pattern measured experimentally by a cooled charge coupled device to as high order as the first order of $|F(\boldsymbol{u})|^2$ [3] and that measured by a photon imaging detector (PID) to the third order were combined together, and the resultant data was processed with the combination of two algorithms [4]; 250 times Hybrid Input Output algorithm (HIO) before 50 times Error Reduction algorithm (ER). For the

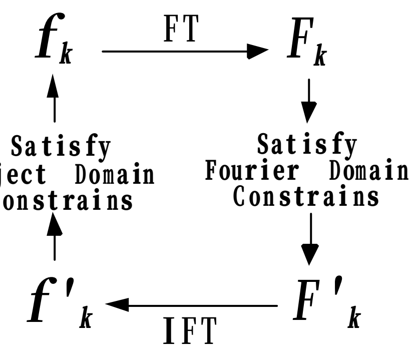


Fig.1 The k th loop of the Fourier Iterative algorithm.
FT: Fourier transform
IFT: inverse Fourier transform

purpose of monitoring the degree of convergence, the object-domain errors E is introduced.; NS presents the domain out of the support domain.

$$E = \sqrt{\sum_{x \in NS} |f'_k(x)|^2 \Big/ \sum_{x} |f'_k(x)|^2}$$

In this paper, more accurate retrieval is aimed for. To accomplish this aim, $|F(\boldsymbol{u})|^2$ is measured accurately with a PID, and the HIO are applied more effectively to the data

2. Experiment

Fig.2 describes an experimental setup of a phase retrieval microscope. The diffracted light wave (wavelength: 633nm) which is measured with the PID travels through a spatial filter, lens, phase object, pinhole. The ND filter included in the spatial filter reduces the intensity of the wave so that no more than one photon is measured by one pixel of PID per 1/30 seconds. The lens is placed at the position where the light wave forms the Fraunhofer diffraction pattern of the object at the PID. The pinhole, of diameter 200 μm, is used as a mask to limit the extent of object field.

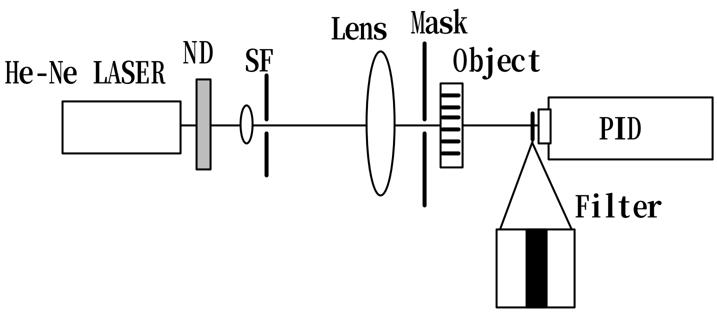


Fig.2 Experimental setup. The filter was placed in front of the PID to attenuate the lower order diffraction spots. ND: ND filter, SF: spatial filter, Mask: pinhole (diameter: 200 μm) PID: Photon Imaging Detector

Fig.3 describes a profile of a part of the phase grating used as an object, whose pitch d, refractive index n, and thickness h are 40 μm, 1.46, and 40 nm, respectively. The optical path difference of about $\lambda/32$ (phase difference 0.06π) is generated by the grating.

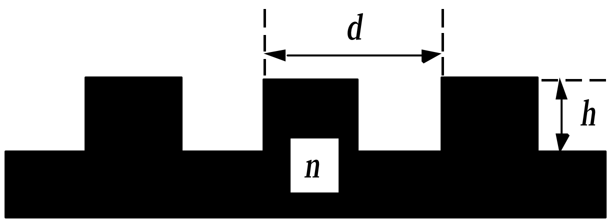
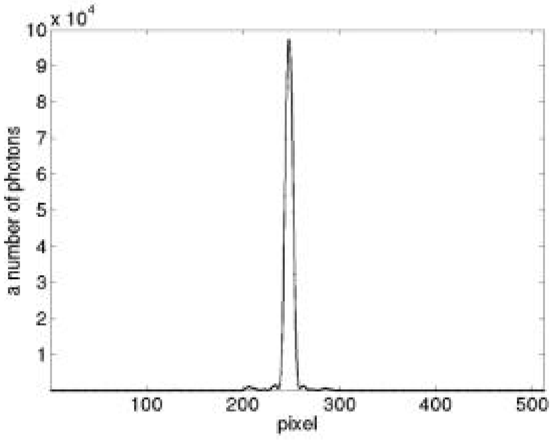


Fig. 3. Phase grating used as an object.
d = 40 μm, h = 40 nm, and n = 1.46.

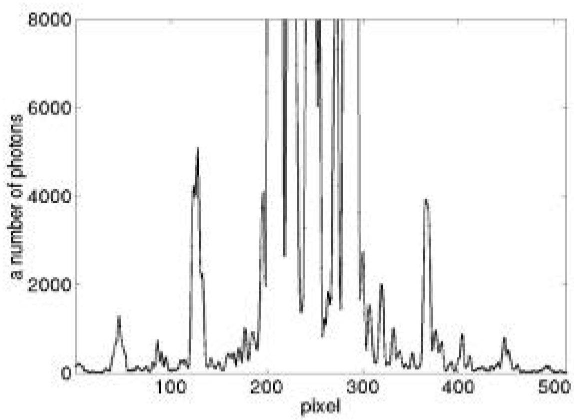
For precise measurement, two types of diffraction pattern were measured. A pattern including the zero order diffraction spot contains about 100,000 photons forming the zero order diffraction spot, and about 1,000 photons for the first order diffraction spot (Fig.4 (a)). The other pattern whose lower order diffraction pattern is attenuated by a filter, and whose higher order diffraction pattern is intensified contains about 5,000 photons for the second order diffraction spot, and 1,000 photons for third order diffraction spot (Fig.4 (b)).

On workstation, the two measured intensity distributions are combined to produce a very wide dynamic range diffraction pattern data that effectively contains about 11,000,000 photons (Fig.4 (c)). Around the central point at which the diffracted intensity is the highest in the combined pattern, the square region containing 384×384 pixels is extracted. The array size of the extracted data was then reduced to 128×128 elements by designating the sum of 3×3 pixels to each element

After normalizing intensities of the pattern, the phase retrieval algorithm was applied to the prepared data.

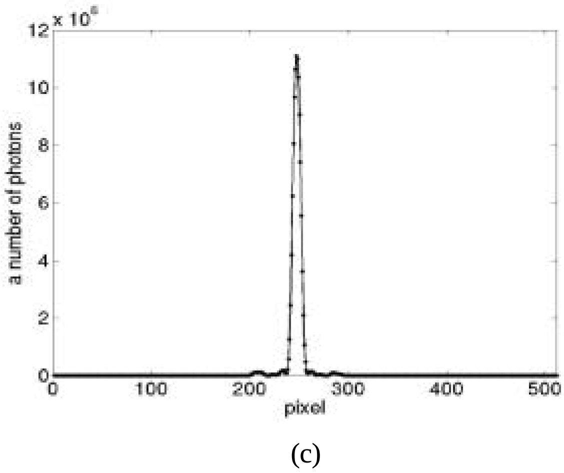


(a)



(b)

Fig.4 Section of the Fraunhofer diffraction intensity patterns measured by the PID, including (a) the zeroth order, (b) higher orders. (c) The combination of (a) and (b).



(c)

3. Phase Retrieval

The phase retrieval algorithm, i.e., 2500 times HIO (feedback parameter: 0.50) before 500 times ER, was applied to the normalized data. As the algorithm proceeds, the error *E* decreases to less than 0.01 (Fig.5), and the object phase distribution was retrieved fairly well as shown in Fig. 6.

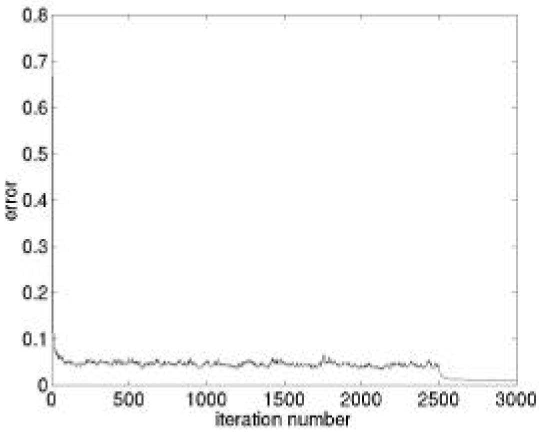


Fig.5 Transition of the error *E*.

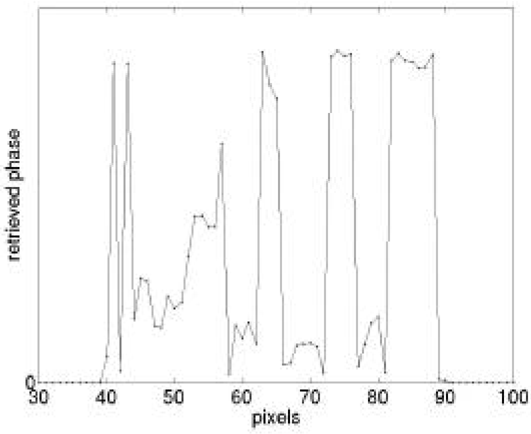


Fig.6 Retrieved phase.
Section of line 100.

4. Conclusion

Measuring a Fraunhofer diffraction pattern including higher order diffraction spots by photon imaging detector, we retrieve the phase of the weak phase object more faithfully than ever.

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