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On Almost Double Resolution Improvement for Off-Axis Electron Holography

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Off-axis electron holography (EH) is currently the most popular and direct experimental technique for precise phase measurements of complex object exit-wave functions created by scattering of coherent electron beams on complex nano-objects studied by the EH in transmission electron microscopy (TEM). Usually, practical resolution of reconstructed phase map is limited by an appropriate Fourier-filter window size applied to one of side-bands of the Fourier transform applied to experimental holograms recorded for different nanoobjects in TEM. The presence of strong autocorrelation spot in typical Fourier-transformed holograms is setting an optimal choice of the Fourier window and, whence, resolution limit, which typically does not exceed 1/2-1/3 of the distance $\boldsymbol{\omega}$ (EH-carrier frequency) between the sideband and autocorrelation maximum in reciprocal space. Even for these optimized conditions the residual "cross-talking" effect between the sideband and central autocorrelation spot may still have a negative effect on the quality of reconstructed phase maps, if the autocorrelation spot appears to be strong and/or carrier frequency too low. Recently, similar problem was examined in light optics and novel solution [1] was suggested on resolution improvement for optical holograms without changing experimental setup.

In present work we examine experimentally and theoretically the idea of orthogonal projections technique [1] and apply it to off-axis electron holograms recorded in TEM with goal to improve the quality and resolution of phase reconstructions by factor of nearly two times. This technique requires recording of second hologram from the same object with electron bi-prizm rotated by ~90 deg. relative to the first hologram. The use of two nearly-orthogonal holograms helps in practical removal of the autocorrelation spot and further extension of the Fourier-filter window size up to distance ~$\boldsymbol{\omega}$, sufficient for double resolution improvement for recovered phase maps without leaking signal to adjacent orders. Our independent model simulations (Fig.1) and first practical EH experiments (Fig.2) performed in TEM agree well with predictions on resolution enhancement of the phase maps recovered by EH without any changes or upgrades into conventional experimental holography set-up.

In Fig. 1 by model simulations we show important steps leading to double-resolution improvement of the recovered phase map (as image of Si[110] lattice) obtained by processing of the orthogonal holograms recorded from the same model object exit-wave function.
As practical example in Fig. 2 we show this approach for phase image resolution enhancement in real TEM/EH experiment performed for tiny polystyrene nano-spheres (diam. ~22 nm) randomly dispersed on thin carbon film by using JEM-2100 microscope equipped with EH bi-prizm. As mentioned above, for both Figs.1-2 the central autocorrelation spot in Fourier-transformed holograms was removed with the help of available orthogonal holograms, thus leading to Fourier-filter window size extension from conventional ~$\boldsymbol{\omega}$/2 towards larger ~$\boldsymbol{\omega}$ radius, accompanied by almost double resolution enhancement in real-space object's phase maps. More practical EH examples will be show at presentation.

[1] P.J. Tavares and M.A. Vaz, *Optics Commun.* ***266*** *(2006) 465-468*
[2] Work was supported by the US DOE, BES (DE-AC02-98CH10886).

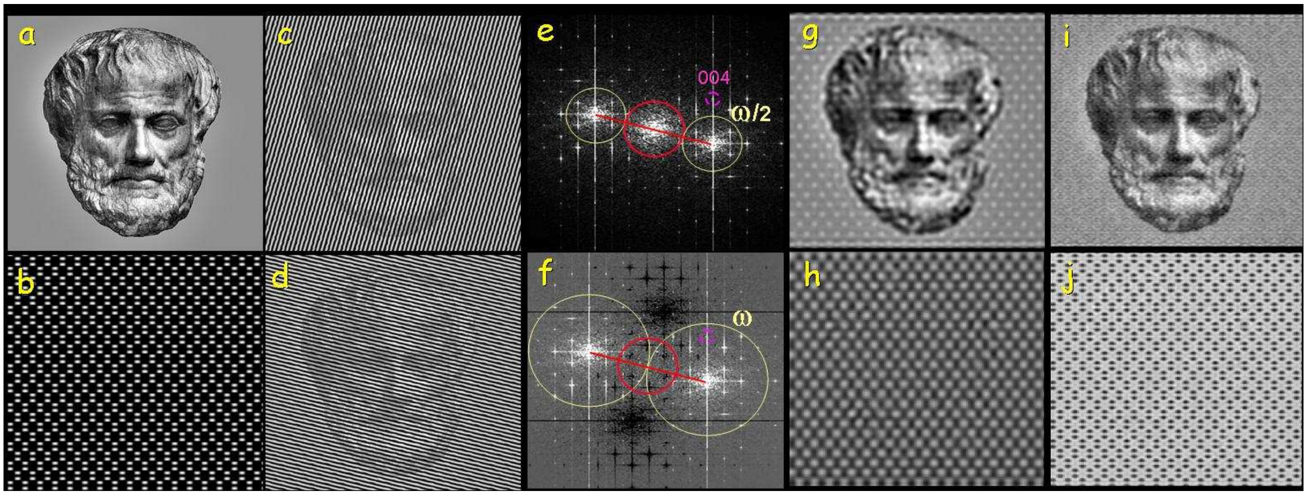

Fig.1. Model calculations illustrating positive effects of double resolution improvement from the recording of two orthogonal holograms of the same object. The reference exit wave (a, b) is presented by amplitude (Aristotle) and phase (Si[110] lattice image). A couple of nearly orthogonal holograms is shown in (c, d). Typical Fourier spectrum (e) of single hologram with central autocorrelation spot is encircled in red color. Removal (f) of the autocorrelation spot shown by red circle with help of two orthogonal holograms (c,d) allows extension of the Fourier filter from traditional ω/2 towards double ω-frequency window size (yellow circles) and, whence, improvement in resolution. Next, some typical ω/2-solution (g, h) is compared to novel holographic ω-solution (i. j) for the same exit-wave function (a, b). Notice that double-resolution improvement allows now resolving all dumbbells d(004) of Si[110] lattice image shown in phase map (j) versus (h) and also greatly reducing unwanted effects of phase "propagation" into new amplitude (i) solution vesus traditional (g) holographic procedure.

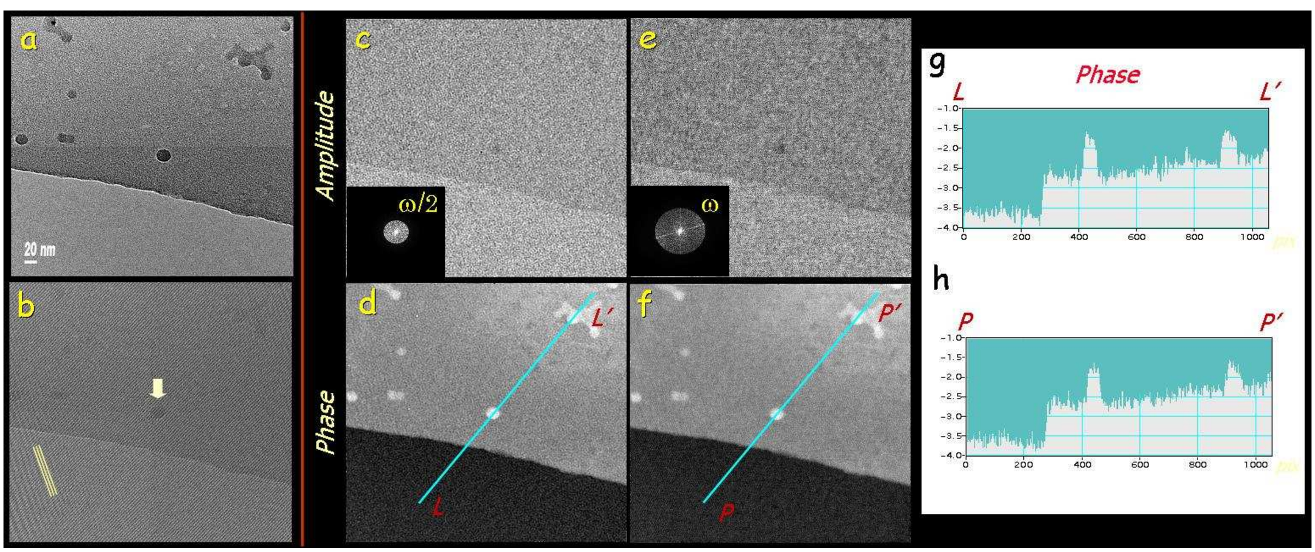

Fig.2. EH experimental data for polysterene nanospheres (marked by arrow in (b)) of ~20 nm size randomly dispersed on thin carbon film: (a) Reference TEM image, (b) One of two orthogonal experimental off-axis holograms. (c,d) Traditional ω/2-solution is compared to novel ω-solution (e,f) with enhanced resolution as illustrated by two line scanes (g, h) respectively across phase maps (d, f). Notice that new (e, f) exit-wave solution shows better amplitude contrast (e) and additional high-frequency features (ω/2→ω) in phase map (f).

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