High precision surface metrology using a phase retrieval method

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Abstract. At wavelength metrology offers a unique opportunity to characterize ultra high quality optics of diffraction limited performance. This technique is based on a coherent interaction of incident wave fields reflected from different surface positions. The mirror surface acts as a phase object which introduces a phase error in the outgoing wave fields. Resultant aberrated wavefront modulates the intensity near the focal plane. The modulated intensity profile can be used to retrieve the mirror shape profile using a numerical phase retrieval method which is developed in the present work. This at-wavelength metrology gives a precise shape information of a mirror having a figure error < 1nm which is extremely difficult to measure with conventional metrology tools.

1. Introduction
In the last decade, a significant improvement has been made in the design of electron accelerators in order to reduce the beam emittance and to increase the photon brilliance. This has increased the coherent properties of the beam and has opened up new branches of microscopy and spectroscopy at nano meter length scales. X-ray nano probe is going to be an important tool for future research, hence numerous work have been carried out to develop a nano focusing optics [1,2] of diffraction limited performance.

To generate a diffraction limited nano meter size beam is a big challenge for an optics designer. It needs a very high quality surface with figure errors less than few nm. This essentially requires ability to selectively suppress the most harmful components of a shape error frequency from a given optics. Another challenge is metrology of aspherical shapes having a figure error < few nm over the full mirror length.

We have developed a numerical approach to derive shape errors from a single intensity distribution of x-rays diffracted by a mirror surface at a focal plane. This method is called “at-wavelength metrology” [3] which is based on coherent interaction of incident wave fields reflected from different surface positions. The mirror surface acts as a phase object which introduces a phase error in the incident coherent wave fields. The resultant wavefields at focal distance generated by coherent superposition of all secondary waves are calculated by Fresnel-Kirchhoff diffraction integral [4]. Practical realization of this technique is rather simple provided the availability of coherent x-ray beam. Nevertheless, it needs a sophisticated computational skill to retrieve the phase information from a single intensity data. This technique is free from the effects of environmental variants like...
temperature, ground vibration etc. It can potentially measure all general class of surfaces with comparable accuracy as achieved with interferometry based techniques.

2. Phase retrieval method
In the at-wavelength metrology process, a mirror surface is required to be illuminated with a wavefront of known shape. The incoming coherent wave field $\psi = A_i e^{i\phi}$ incident at a distance $r_0$ on the mirror surface is then reflected from different surface positions with a certain aberrations introduced by shape errors. The aberrated wavefields modulate the intensity profile near the focal plane. This wavefields at distance $r_1$ generated by coherent superposition of all secondary waves is calculated by Fresnel-Kirchhoff diffraction integral

$$I(r_1) = \left| \psi(r_1) \right|^2 = \left| \int_{-\infty}^{\infty} \psi_A(x) \cdot e^{i\phi} \cdot e^{i\psi} \cdot dx \right|^2$$

where $\psi_A(x)$ is the wavefield at the incident slit, $\phi$ is the phase difference, $\gamma$ is the oblique angle of wavefield with respect to aperture normal, $k$ is wave vector and $\lambda$ is wavelength. The wavefield error $\Phi$ is connected with surface height error $h$ in grazing incidence geometry by

$$\Phi = 2\pi h \cdot \sin \theta$$

The above integral formula well explains the interference fringes arising from wavefields reflected from different surface heights and gives a powerful method for figure error analysis in term of “at wavelength metrology”.

Interpretation of intensity data measured near the focal plane is not obvious but needs a sophisticated algorithm of phase retrieval. Such algorithms have been developed earlier [5,6] but they are not in the form to be used for general optical metrology. In the present work a numerical algorithm has been developed to retrieve the phase from a single intensity measurement at a focal point. The method is based on the iterative phase transform scheme where the calculated intensity at focal point is replaced in each iteration by experimental values and keeps the calculated phase for next iteration. The loop works until the calculated intensity matches well with the experimentally measured values. Flow chart of the approach has been explained in the Figure 1.

3. Results and discussions
We have used an actual shape error data of a 64 mm length elliptical mirror measured with a long trace profilometer (LTP) to calculate the intensity profile according to the parameters given in Table 1.
To test the effectiveness of the developed phase retrieval algorithm this intensity data is used to retrieve the phase information. The intensity profile obtained at 60 nm focal distance assuming zero shape error gives a focus size of 22.86 nm FWHM.

This mirror had an actual shape error of 8 nm peak to valley (PV). The PV height error is rescaled from 1 nm to 8 nm in order to generate different intensity profiles at the focal spot. All these intensity profiles are plotted in Figure 2 (left) and corresponding figure error profiles are also given in the adjacent curves (right).

For the present configuration (see Table I), the Rayleigh criteria of $\lambda/4$ requires the figure error below 3.33 nm PV to achieve the diffraction limited focal spot. It is evident that the intensity distribution at the focal plane remains symmetric for figure error less than 3.33 nm PV. For the figure errors of 4nm and above the intensity profiles suggest a degradation of focusing performance.

To test our phase retrieval scheme the intensity profiles data corresponding to 1nm, 2nm, 4nm and 8nm PV are used to retrieve the corresponding shape error profiles. The algorithm given in above flow chart is implemented in the Labview platform, which operates in Windows environment. In this program the iterative phase transform loop executes till the Chi square value attains a defined figure of merit criterion. For all these four intensity profiles the corresponding shape errors are retrieved in 30-50 iterations. In Figure 2, retrieved intensity and shape curves are shown by continuous lines. The retrieved shape errors are in well agreement with the profiles measured with LTP. This agreement is found to be excellent. The error between true and retrieved profile is found to be less than 0.25nm or better. The results are very encouraging and efforts are underway to improve it further.

4. Conclusions
At wavelength metrology is a promising tool for characterizing optics of diffraction limited performance. The method needs just an intensity data to recover the shape error profile. The technique involves a simple instrumentalational approach provided that a coherent beam on any synchrotron source is available. A sophisticated computational skill is essential for efficient phase retrieval. The technique is easy to apply on variety of surfaces and shapes.

5. References
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