Effect of Focusing Optics on X-ray Speckle Contrast

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Abstract. We investigated the behavior of speckle contrast and size under various experimental conditions using 1.82 keV x-rays. In this paper, we report the comparison of two different setups for x-ray speckle experiments: one employing a focusing zone plate and one in which a pinhole selects the size of the coherent x-ray beam. We found a strong dependence of the speckle contrast and size on the type of setup. In general, the pinhole setup results in higher contrast but smaller speckle size. On the other hand, the zone plate setup allows one to target much smaller areas of interest in the sample, down to submicron dimensions, and also to adjust the speckle size. We anticipate that these results will be useful in future time-correlation spectroscopy experiments.

A disordered system illuminated with temporally and spatially coherent light produces a speckle pattern, which is an interference pattern of all the waves scattered by the various scattering centers in the sample. To a first approximation the average shape of a speckle in an experiment with a circular aperture is an Airy pattern (1),

$$I \propto \left|\left(\frac{2J_1(v)}{v}\right)\right|^2, \quad v = \frac{D}{2}\Delta q, \tag{1}$$

where D is the diameter of the illuminated spot on the sample and Δq is the radial distance from the center of the speckle in momentum transfer q. Therefore, the average full-width at half-maximum (FWHM) size of a speckle is approximately $2\pi/D$, being inversely proportional to the illuminated spot size.

We explored two different scattering geometries at the SRI-CAT beamline 2-ID-B at the Advanced Photon Source: a pinhole setup (Figure 1a) and a zone plate setup (Figure 1b). Details of the beamline can be found elsewhere (2). So far, only pinhole setups are used routinely in x-ray speckle experiments (3,4). However, a zone plate

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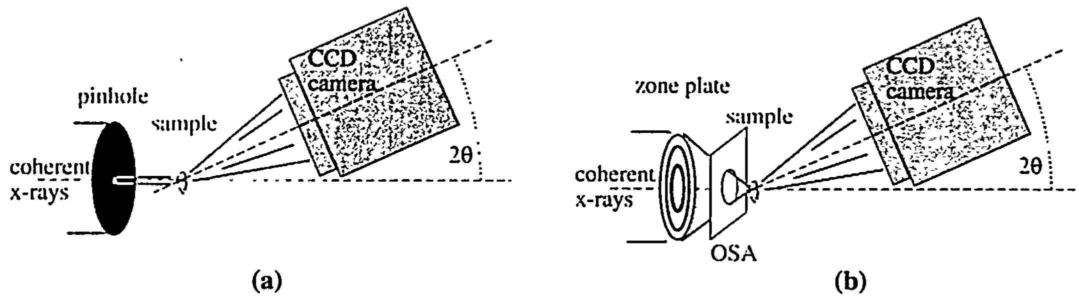


FIGURE 1. Experimental configurations used: the pinhole setup (a) and the zone plate setup (b).

setup may be useful for adjusting the speckle size in the recorded pattern by changing the size of the beam on the sample. For our measurements, a photon energy of 1820 eV was used. The calculated transverse coherence length of the incident beam was 68 μm in diameter at the experiment (5). In the pinhole setup, a 5-μm-diameter pinhole ~5 mm upstream of the sample was used to select a small coherent area from the beam. In the zone plate setup a 77-μm-diameter zone plate having a 100-nm finest zone width (giving a focal length of 11.3 mm) was nearly coherently illuminated to focus the beam. An order-sorting aperture (OSA) of 20 μm diameter downstream of the zone plate selected the first-order focused beam. In both cases, a guard slit (not shown) directly in front of the sample allowed us to block parasitic scattering from the pinhole (a) or the OSA (b) in the area of the pattern used for analysis. The scattered intensity, the speckle pattern, was recorded with a thinned, backside-illuminated CCD camera located 517 mm downstream of the sample.

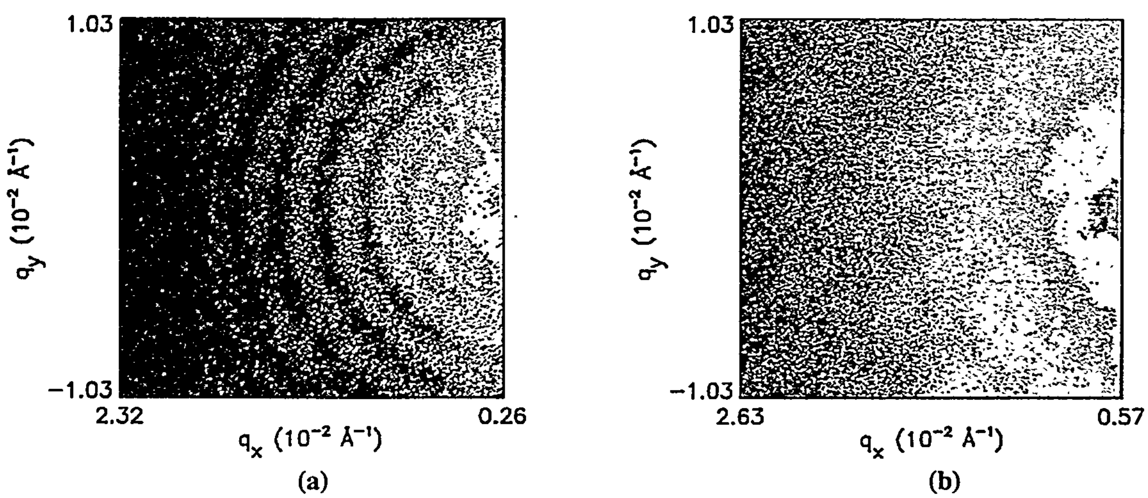
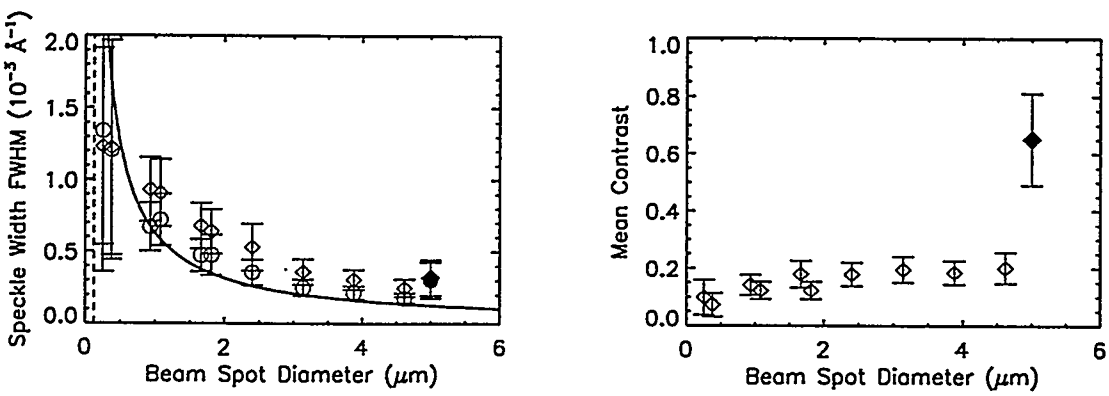


FIGURE 2. Speckle pictures obtained with the two different setups: pinhole (a), and zone plate (b). The sample consisted of dried polystyrene latex spheres. For (b), the sample was near the focus of the zone plate. The streak seen in figure (a) results from parasitic scattering.

Speckle patterns were obtained from dried 266-nm-diameter polystyrene latex spheres using both the pinhole setup and the zone plate setup. Examples are shown in Figure 2. In the zone plate setup, the sample was almost at the focus. The rings evident in the pinhole pattern arise from the form factor of the latex spheres (not the pinhole). For the pinhole pattern, the speckle size is much smaller than the width of these rings, while for the zone plate pattern the speckle size is similar to the ring width, so the rings are not resolved. The zone plate setup produces speckles which subtend a larger angle because of the smaller size of the illuminated area on the sample (~256 nm FWHM in this case). Thus, the detector could be placed closer to the sample for the same resolution (pixels/speckle), which would offer the possibility to record a larger range in momentum transfer q.

The speckle width and contrast obtained using the pinhole setup, and the zone plate setup with various distances between the sample and the zone plate, are shown in Figure 3. These were obtained by averaging over a region of each pattern having a q range between 0.005 and 0.017 $Å^{-1}$; any q dependence is reflected in the error bars shown. Figure 3a shows the average speckle widths observed in the azimuthal and radial directions as a function of the diameter of the beam spot on the sample. For the zone plate case, the actual size of the spot on the sample during the experiment was not measured. Instead we calculated it from the zone-plate-to-sample distance, using the intensity distribution in the vicinity of the focus of a lens (6), taking the FWHM of the flux as the beam spot diameter. This calculation is probably not correct near the focus, because we did not illuminate the zone plate fully coherently. Therefore, the actual beam spot size may have been slightly larger than shown at the smallest values. According to equation 1, we expect larger speckles for smaller illuminated areas on the sample. The solid line in Figure 3a describes this relationship. The observed speckle sizes agree within the error bars with this simple calculation. The observed radial speckle size was consistently larger than the azimuthal one. This effect was



(a) (b)

FIGURE 3. Comparison of the two setups: pinhole (filled symbols) and zone plate (open symbols): Figure (a) shows the observed speckle FWHM in q versus the spot diameter of the beam on the sample (azimuthal: circles, radial: diamonds). The vertical, dashed line describes the beam spot diameter at the focus of the zone plate. The solid line represents the calculation according to equation 1. Figure (b) shows the observed contrast versus spot size on the sample.

observed previously in cases of limited monochromaticity (3,4). However, the monochromaticity $\lambda/\Delta\lambda$ (λ being the wavelength) for our zone plate setup was on the order of 460, which is not expected to result in a significant radial broadening (3). It is surprising that the high divergence introduced by the zone plate does not increase the speckle widths. Instead, the observed speckle sizes from the zone plate are approximately given by that calculated from the diameter of the illuminated area on the sample. If the divergence introduced by the zone plate (6.8×10^{-3} rad) was treated in the same way as the source divergence in a pinhole setup (3), we would expect the observed speckle size to be smeared out to about 9×10^{-3} Å^{-1}, independent of the diameter of the beam spot on the sample. Nevertheless, the small differences between the radial and the azimuthal widths may be due to focusing.

We also measured the dependence of the average contrast on the spot size (Figure 3b). Here, contrast is defined as the height of the background-subtracted normalized spatial autocorrelation function (3). Note that this definition is equivalent to the square of the standard deviation of the intensity over the square of the mean intensity. The contrast in the pinhole setup was significantly higher than the contrast in the zone plate setup. We speculate that this could be due to the difference in the coherent illumination of the 5-μm pinhole and the 77-μm zone plate or the background produced by the other zone plate orders, mainly zeroth, passed by the OSA. Note that the contrast did not decrease even for small speckle widths (large beam spots) in the zone plate setup, further evidence that the divergence introduced by focusing did not increase the speckle width. The decrease in contrast towards small beam spot diameters on the sample probably had to do with the extreme aspect ratio of sample thickness to beam spot diameter on the sample in this regime. For the smallest spot size we investigated in these measurements, the aspect ratio was about 100:1.

In conclusion, the zone plate setup allows one to control the size of the speckles over a wide range. The divergence introduced by the focusing does not directly affect the observed speckle size or contrast. Using a zone plate to change the speckle sizes can decrease the required sample-to-detector distance while maintaining the same spatial detector resolution per speckle. Consequently, for a fixed detector the range of access in momentum transfer q will be extended. With the same sample-to-detector distance, the two setups access the same range in q. A small spot size on the sample can be useful if targeting of small sample areas is desired. Additionally, by focusing the beam, the zone plate setup can increase the flux per speckle, which may be important in time correlation experiments. On the other hand, the pinhole setup provides better resolution in q. The resolution obtained from our pinhole data is $\Delta q \approx 6.16 \times 10^{-4}$ Å^{-1} with a 5-μm pinhole to select the coherent area.

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REFERENCES

1. Goodman, J.W., "Statistical Properties of Laser Light Patterns," in *Laser Speckle and Related Phenomena*, edited by J.C. Dainty, Berlin, Springer-Verlag, 1984, pp. 9-75.
2. McNulty, I., et al., *Rev. Sci. Instrum.* 67, CD-ROM (1996); McNulty, I., et al., *SPIE Proc.* **3150**, 195 (1997).
3. Abernathy, D. L., et al., *J. Synchr. Rad.* **5**, 37-47 (1998).
4. Sutton, M., et al., *Nature* **352**, 608-610 (1991); Cai, Z.H., et al., *Phys. Rev. Lett.* **73**, 82-85 (1994); Brauer, S., et al., *Phys. Rev. Lett.* **74**, 2010-2013 (1995); Dierker, S.B., et al., *Phys. Rev. Lett.* **75**, 449-452 (1995); Thurn-Albrecht, T., et al., *Phys. Rev. Lett.* **77**, 5437-5440 (1996); Mochrie, S.G.J., et al., *Phys. Rev. Lett.* **78**, 1275-1278 (1997); Tsui, O.K.C., and Mochrie, S.G.J., *Phys. Rev. E* **57**, 2030 (1998); Malik, A., et al., *Phys. Rev. Lett.* **81**, 5832-5835 (1998); Sandy, A.R., et al., *J. Synchr. Rad.* **6**,1174-1184 (1999).
5. Born, M., and Wolf, E., *Principles of Optics*, Cambridge University Press, 1980, ch. 10, pp. 508-513.
6. Born, M., and Wolf, E., *Principles of Optics*, Cambridge University Press, 1980, ch. 8, pp. 435-449.