A four-channel multilayer KB microscope for high-resolution 8-keV X-ray imaging in laser-plasma diagnostics

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A four-channel multilayer Kirkpatrick-Baez (KB) microscope is developed for the 8-keV X-ray imaging of experiments on laser inertial confinement fusion (ICF). A periodic multilayer that works at 8 keV and with a grazing incidence angle of 1.0° is coated on reflective surfaces to achieve a spatial resolution higher than 5 μm and an effective solid angle higher than $\sim 10^{-7}$ sr. A precise assembly is realized by a conical reference cone to couple with an X-ray framing camera. This study provides detailed information on an optical and multilayer design, assembly method, and experimental results with a Cu X-ray tube. The instrument provides a high-resolution and high-throughput X-ray image for backlit or self-emission imaging of laser plasma at Cu Kα line radiation in Shenguang series laser facilities.

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X-ray imaging is a useful method in the plasma diagnostics of laser inertial confinement fusion (ICF). The detailed spatial and temporal (Δt=35−100 ps) evolution of plasma density or temperature can be obtained through high-resolution two-dimensional X-ray framed imaging of laser-produced plasma in backlit or self-emission mode. Four-channel Kirkpatrick-Baez (KB) microscopes that provide a better spatial resolution (3−5 μm in several hundred microns field of view) and a larger collecting solid angle ($\sim 10^{-7}$ sr) than X-ray pinhole arrays have been used in ICF experiments to observe precise physical processes, such as hydrodynamic instabilities and evolution of distortions in the implosion of the ICF target[1]. These instruments use the total external reflection of single-layer metal coatings (e.g., Ir or Pt) on the reflective surface, and the working energies are mainly in the soft X-ray region, such as 1.25 keV (U N-band) for X-ray backlighter[2] and 2.79 keV (Cl He-like Ly α) for X-ray self-emission[3].

With the increased target mass in integrated ignition experiments of high-power laser facilities[4], the plasma is optically thick for soft X-rays to penetrate the target. Using hard X-rays (e.g., 8-keV, Cu Kα line) with a large penetration depth is more feasible than using soft X-rays[5−8]. For X-ray backlit imaging, 8-keV X-rays can penetrate high-density regions while separating from the low-energy self-emission of the imploded ICF target. For X-ray self-emission imaging, the 8-keV X-rays produced from Cu tracer layers can easily escape the dense ICF target. The 8-keV X-ray response of KB microscopes can be obtained by single-layer metal coatings, but the grazing angle must be smaller than the critical angle of total external reflection, which limits the spatial resolution[9]. Friesen *et al.*[10] developed a single-channel KB microscope for the 8 keV X-ray imaging of fast ignition experiments in Titan laser facility. The 25.4-mm diameter reflective surfaces with a curvature radius of 20 m were coated with Pt and operated at a grazing angle of 0.5°. The actual spatial resolution is only 15 μm in the center field and 30 μm over the 300 μm object field. Multilayer coatings based on Bragg diffraction $2D\sin\theta=m\lambda$ are a good solution to achieve a large grazing angle with a narrow high-throughput bandpass[11]. Marshall *et al.*[12,13] designed a four-channel multilayer KB microscope that is capable of imaging X-ray emission in the range of 7−9 keV. The reflective surfaces with a curvature radius of 28 m were coated with W/B$_4$C multilayer and operated at a grazing angle of ~0.7°. The measured peak reflectivity was up to 80% at a grazing angle of 0.72°, and an X-ray image with a 5-μm resolution over a ~400 μm object field was obtained.

In this study, we develop an 8-keV four-channel multilayer KB microscope for X-ray imaging diagnostics in Shenguang series laser facilities. Firstly, we describes the optical design of the four-channel multilayer KB microscope and the assembly method to accurately control image separations on the image plane because of the limited detector size of the framing camera. Then, we attempt to maximize the response of 8 keV through the coincidence of the grazing angles between nominal and actual values. At last, we describes the 8-keV X-ray experiments and the imaging results of the four-channel KB microscope, followed by a brief conclusion and discussion of its possible applications.

The KB microscope consists of two perpendicular concave spherical mirrors in tandem. The imaging equation of each mirror in the meridian plane is given by[14]

$$\frac{1}{u}+\frac{1}{v}=\frac{1}{f}=\frac{2}{R\cdot\sin\theta}, \tag{1a}$$

$$u=\frac{R\sin\theta}{2}\left(1+\frac{1}{M}\right), \tag{1b}$$

where u is the object distance from the target to the mirror center, v is the image distance from the mirror center to the image plane, f is the focus distance, R is the radius of curvature of the mirror, θ is the grazing incidence angle, and $M=v/u$ is the magnification. The spatial resolution expressed by lateral aberration and the geometric collecting solid angle expressed by the solid angle are respectively given by[9,11]

$$\delta=\frac{3d^2}{8R}+\frac{d}{R\cdot\sin\theta}\cdot q, \tag{2}$$

$$\Omega=\left(\frac{d\cdot\sin\theta}{u}\right)^2=\left[\frac{2d}{R\left(1+1/M\right)}\right]^2\approx\left(\frac{2d}{R}\right)^2, \tag{3}$$

where d is the mirror length along the optic axis, and q is the object field of view. The first term on the right-hand side of Eq. (2) is the primary on-axis spherical aberration, which determines the best achievable spatial resolution of the KB microscope, and the second term is the obliquity of the field. The values of the above-mentioned parameters should be determined by both the resolution requirement and the actual flux. The radius of curvature and the length of each mirror are selected to be ~20 m and 10 mm, respectively, which are similar to those in Ref. [11], to achieve a spatial resolution better than 5 μm in the central field and a geometric solid angle of $\sim 10^{-6}$ sr. The reflectivity of X-ray multilayer mirrors affects the effective solid angle. Therefore, the grazing incidence angles of the X-ray multilayer mirrors were selected at ~1°, and the effective solid angle was up to 2.5×10^{-7} sr under an X-ray multilayer reflectivity of 50%. Meanwhile, Eq. (2) shows that off-axis aberration is improved under a grazing incidence angle larger than those in Refs. [10,12]. The magnification was selected to be ~10× because a small magnification would lead to a relatively high intensity in the image plane, although the actual spatial resolution was limited by the pixel size of the image detector. The spatial resolution simulated by the ray-tracing method with the use of Zemax software decreases near-linearly from 2 μm at the central field to near 8 μm at the ±200-μm object field.

The four-channel KB microscope shown in Fig. 1(a) utilizes four concave spherical mirrors stacked in two perpendicular pairs to form four images of the ICF target. The instrument also follows Eqs. (1)−(3), but X-ray images must be separated to specific distances to couple with the microstrips of the framing camera. If common assembly methods based on optical contact are used, the image separations of the instrument are up to 57 mm, which exceed the maximum detector size (Φ=36 mm) of the existing framing camera on Shenguang series laser facilities[15]. The assembly method of the four-channel KB microscope we used is similar to that in Ref. [16], which uses ball plungers to press the concave mirrors on the rectangular conference core. However, the rectangular reference core was improved as a conical one with angle α to control the image separations ($2L$) at a specific value of 20.0 mm. The geometric relations of the four-channel KB microscope in the meridian plane are given by Fig. 1(b) with the following equations:

$$\begin{aligned} y = {} & R\cdot\cos\alpha-u\cdot\sin\left(\theta+\alpha\right) \\ & -\sqrt{R^2-\left(d\cdot\cos\alpha+R\cdot\sin\alpha\right)^2}, \end{aligned} \tag{4}$$

$$L=u\cdot\left[M\cdot\sin\left(\alpha-\theta\right)-\sin\left(\alpha+\theta\right)\right]. \tag{5}$$

The best object field of the four channels must be located at the same position because of the rapid decrease in spatial resolution at the off-axis field. However, an error in the radius of curvature (ΔR) from manufacturing leads to deviations in the best object field of different channels. This error can be compensated by a precise spatial alignment and the resulting change in the grazing angle. Equation (1b) shows that the grazing angle will have the same change of ~0.05° if $\Delta R/R$=5%, which significantly influences the reflect efficiency of the 8-keV X-ray multilayer with a narrow angular width of ~0.1°. Therefore, the optical parameters of the four-channel KB microscope as listed in Table 1 were designed according to the measured results of the radius of curvature. As measured by an optical profiler (Contour GT-X3, Bruker, USA), the mean curvature radius of the four concave mirrors is 19.5 m with an root mean square (RMS) variation of 0.3 m, which corresponds to a grazing angle change of ~0.015°. The conical reference cone has a thickness of $2y$=13.515 mm and a conical angle α=1.193° in the meridonal direction and $2y$=15.183 mm and α=1.248° in the sagittal direction. The thickness and angle accuracy $\Delta(2y)$ and $\Delta\alpha$ of the conical reference core can

Table 1. Optical Parameters of the Four-Channel KB Microscope

Direction	R(m)	M	θ(°)	d(mm)	u(mm)	v(mm)	Ω_{geo}(sr)
Meridian	19.5	10.0×	0.9730	10.0	182.1	1821.0	8.0×10^{-7}
Sagittal		9.3×	1.0310		194.1	1809.0	

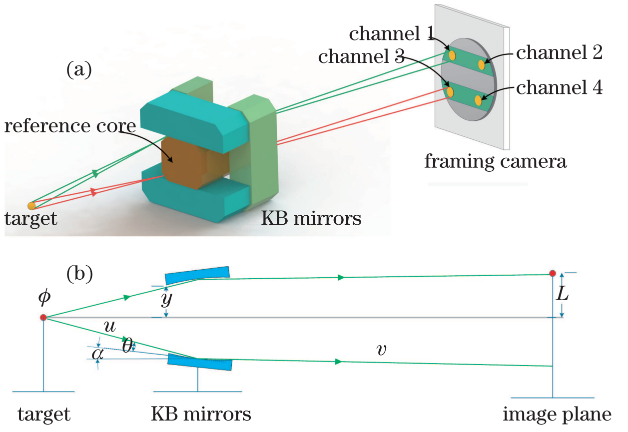

Fig. 1. Schematic of the four-channel KB microscope. (a) Optical structure for time-gated X-ray imaging. (b) Geometric parameters determine image separations in the meridian plane.

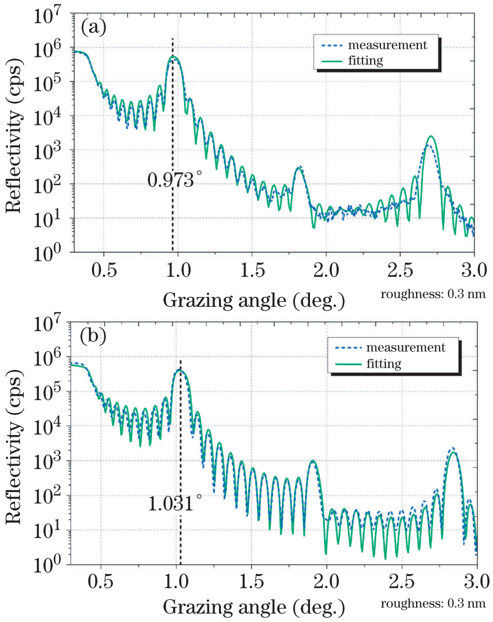

Fig. 2. Measured (dashed) and fitted (solid) grazing incident X-ray reflectivity curves of W/C periodic multilayers deposited onto KB mirrors. The incident X-ray is from a Cu tube that works at 8 keV (Kα line). The first Bragg peaks are shown for grazing angles of (a) 0.973° and (b) 1.031° with period thicknesses of D1=4.80 nm and D2=4.56 nm, respectively.

easily reach 20 μm and $10''$, respectively, as observed under a vernier caliper and goniometer. The influence of the conical reference core on the change of the best object field is negligible.

We utilized W/C periodic multilayers to achieve a grazing angle of up to ~1° at 8 keV. The W/C multilayers were coated on the reflecting surfaces of concave mirrors for grazing angles of 0.973° and 1.031°, with a period thicknesses of D_1=4.80 nm and D_2=4.56 nm, respectively. The bi-layer number of both multilayers is 12. The surface roughness of the concave mirrors substrates is ~0.3 nm (RMS, measured with an atomic force microscope). The multilayer was deposited with the use of direct current magnetron sputtering technology. The base pressure before deposition is 5.0×10^{-5} Pa. Argon gas was used as the working gas with a constant pressure of 0.2 Pa during deposition. The powers of the W and C targets are 20 and 120 W, respectively.

The experimental reflectivities of the W/C multilayers coated on KB mirrors were measured by an X-ray diffractometer (D1 System, Bede Scientific Inc., UK), as shown in Fig. 2. The measured reflectivity curve was fitted with the use of REFS, a genetic algorithm program provided by Bede Scientific Inc.. Instrumental beam divergence was also considered in the fitting model because it will broaden the reflection peak in measurement. The fitted curve is also shown in Fig. 2. The simulated curves fit the measured ones very well in both height and shape. The fitting results indicate the deposited layer thicknesses, which can be reduced by precise calibration of the deposition rate. The deposited multilayers coincide with the design.

The reflectivities are ~50% at designed grazing angles of 0.973° and 1.031° with an angular bandwidth of ~0.1°. These angles correspond to the ~300 μm object field and can fulfill the requirements of the KB microscope. The grazing angle change of ~0.015° caused by the measurement error of the radius of curvature (0.3 m RMS) corresponds to a decrease in reflectivity of ~2%.

X-ray imaging experiments of the four-channel KB microscope in the laboratory are essential before the microscope can be used for ICF experiments. The best object field and the actual spatial resolution can be characterized by X-ray imaging results. A 600# Au grid (42.0-μm period with 6−7-μm line width calibrated by scanning election microscope (SEM)) simulated a resolution pattern and was backlit by a copper X-ray tube (8 keV) operated at 37.5 kV and a tube current of 20 mA. A scintillator X-ray CCD (XDI-50, Photonic Science, UK) with 696 × 520 pixels and 12.9 × 12.9 (μm) pixel size was placed on the image plane. The distance between four X-ray images was controlled at 20 mm by a motorized x-y-z axis translation stage fixed with X-ray CCD. Figure 3 shows the imaging results of the grid obtained by the four-channel KB microscope after the assembly, in which the exposure time is 20 min with 83 gain. The ununiformed brightness is due to the X-ray source, which has been tested by direct projection. A hole with about 150-μm diameter in the grid was used as a reference of the best object field and the image separations. The actual hole separations between four channels were ~20.2 and ~18.8 mm in the horizontal and vertical directions, respectively, which were in good agreement with the designed value of 20.0 mm.

The image of the Au wire is very clear in the central field (the reference hole) and gradually blur out as the field of view increases. Figure 4(a) shows the intensity distribution of channel 2 along the horizontal direction. The actual magnification of the four-channel KB microscope can be calculated by comparison of the period of the grid imaged by CCD and that calibrated by SEM. The value is 9.68× and 9.17× in the horizontal and vertical directions, respectively. The measured spatial resolution of channel 2 is shown in Fig. 4(b), which corresponds to a distance of 10% to 90% of the minimum intensity to the maximum intensity. It is approximately 5 μm within ±100-μm object field and better than 10 μm

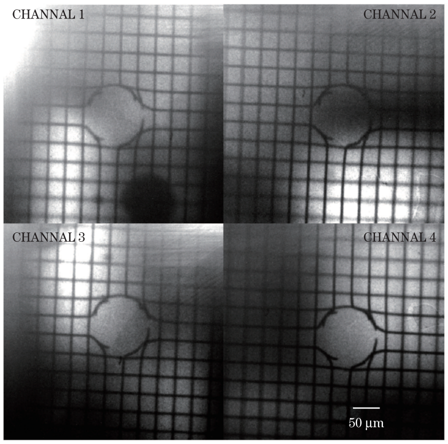

Fig. 3. Four images of a 600# Au grid obtained by the four-channel KB microscope at 8 keV. The distance between the four images is controlled to 20 mm by a motorized x-y-z axis translation stage fixed with X-ray CCD.

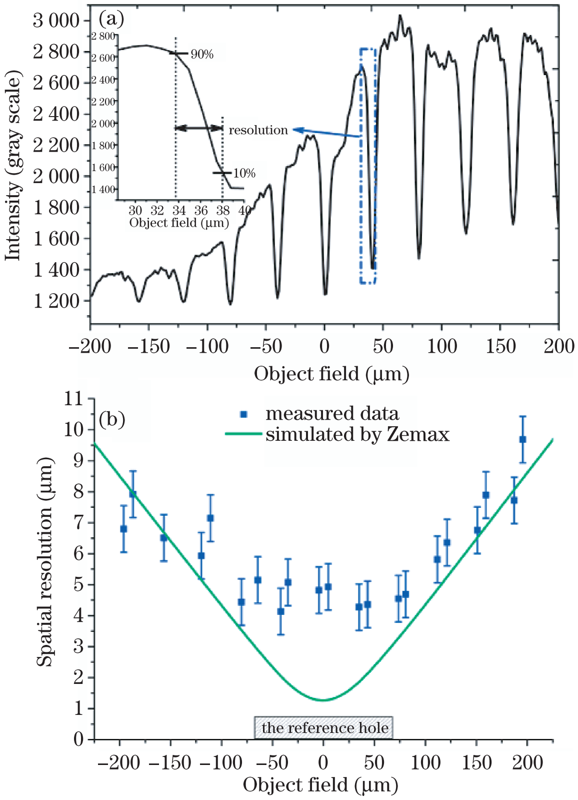

Fig. 4. Image quality of a 600# Au grid obtained by the four-channel KB microscope at 8 keV. (a) Intensity distribution of channel 2 in the sagittal direction. (b) Comparison of the measured and simulated spatial resolutions of channel 2.

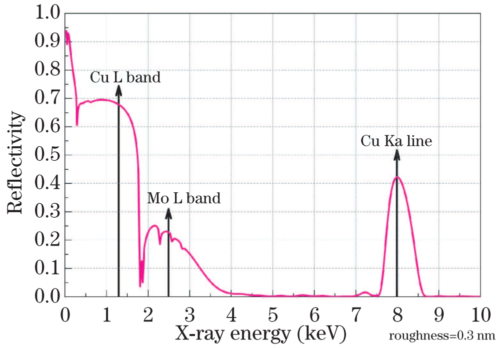

Fig. 5. Theoretic energy response of the four-channel KB microscope.

within ±200-μm object field. The simulated resolution by Zemax is also shown in Fig. 4(b). The image quality is influenced by the diffraction effect, figure error, and surface roughness of the concave spherical mirrors, especially for the central field. An improved spatial resolution can also be achieved by the X-ray CCD with a small pixel size.

In conclusion, a four-channel multilayer KB microscope for the high-resolution 8-keV X-ray imaging of experiments on laser inertial confinement fusion is investigated. A spatial resolution of 4-6 μm within the ±200-μm object field is achieved in the X-ray experiments. The precise control of image separations of the four-channel KB microscope is realized by a conical reference cone, which also has the ability to reflect soft X-rays lower than 3 keV. Figure 5 shows the energy response of the instrument subtended by two reflections of KB mirrors. The reflectivities at 1.25 keV (U N-band) and 2.5 keV (Mo L-band) are higher than 60% and 20%, respectively. Therefore, the instrument is also applicable to soft X-ray imaging diagnostics, such as measurements of the growth rate of Rayleigh-Taylor instability and implosion trajectory of a hohlraum-radiative-driven capsule[2,17].

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