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Instantaneous electron beam emittance measurement system based on the optical transition radiation principle*

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Abstract: One kind of instantaneous electron beam emittance measurement system based on the optical transition radiation principle and double imaging optical method has been set up. It is mainly adopted in the test for the intense electron-beam produced by a linear induction accelerator. The system features two characteristics. The first one concerns the system synchronization signal triggered by the following edge of the main output waveform from a Blumlein switch. The synchronous precision of about 1 ns between the electron beam and the image capture time can be reached in this way so that the electron beam emittance at the desired time point can be obtained. The other advantage of the system is the ability to obtain the beam spot and beam divergence in one measurement so that the calculated result is the true beam emittance at that time, which can explain the electron beam condition. It provides to be a powerful beam diagnostic method for a 2.5 kA, 18.5 MeV, 90 ns (FWHM) electron beam pulse produced by Dragon I. The ability of the instantaneous measurement is about 3 ns and it can measure the beam emittance at any time point during one beam pulse. A series of beam emittances have been obtained for Dragon I. The typical beam spot is 9.0 mm (FWHM) in diameter and the corresponding beam divergence is about 10.5 mrad.

Key words: optical transition radiation, beam emittance, double-imaging, linear induction accelerator, instantaneous measure

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1 Introduction

The electron beam divergence is an important parameter for the commissioning and study of the linear induction accelerator (LIA). The transition radiation (TR) will occur when a charged particle crosses a boundary between media with different dielectric constants; the optical transition radiation (OTR) means that the emitted energy is within the visible light spectrum. The beam emittance measurement technique using OTR features high spatial resolution, ultra-fast response and multi-parameter measurement at one time. It has been widely developed in the study of high intensity electron beams and accelerators. A time-resolved measurement system using OTR for an electron beam of high energy and high intensity has been developed in the Institute of Fluid Physics [1]. In order to capture a beam spot image and beam divergence image at one time, a set of instantaneous electron beams emittance measurement system based on the OTR principle and double imaging optical method has been established for diagnostics of the pulsed, high intensity beam (2.5 kA, 18.5 MeV, 90 ns) produce by Dragon-I LIA. It is able to capture the beam spot image and beam divergence image at the same time with a 3 ns shutter time and can capture two images in sequence with the interval time of about 5 ns. The real beam emittance is then obtained and this result features relative instantaneity. The following edge of the output waveform of blumlein lines in the pulsed-power system is adopted as the trigger signal for the measurement system so the measured synchronization accuracy of about one ns can be reached [2]. The instantaneous measurement can capture an electron beam spot image and divergence image at any time of the pulse with a very short shutter time if some delay methods are taken. The typical beam spot is 9.0 mm (FWHM) in diameter and the corresponding instantaneous beam divergence is about 10.5 mrad.

Many factors, such as beam energy, beam spot size, working distance, measurement system field layout and so on, must be taken into account while designing the system structure. The OTR lens design is the most difficult design work in the system because of the double-imaging method and the working conditions. The most suitable

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tradeoff between lens focus length, lens diameter and device layout must be chosen in order to obtain an excellent synthesized performance. The system structural design and parameters' calculations will be discussed in detail in this paper.

2 The OTR principle and the instantaneous emittance measurement principle

We will review the basic physics for OTR from a single foil. When an electron incidence onto the surface of metal at 45° from a vacuum, the backwards OTR distribution can be expressed as the following formula when the parallel case is discussed [3]

$$\frac{\mathrm{d}^2W}{\mathrm{d}\omega\mathrm{d}\Omega}=\frac{e^2\beta^2}{16\pi^3\varepsilon_0 c}\frac{\sin^2\theta}{(1-\beta\cos\theta)^2}, \tag{1}$$

where ω is the photon frequency, Ω is the solid angle, θ is the angle of observation direction relative to the specular reflection of the particle velocity, β is the relativistic velocity factor for the electron, ε_0 is the vacuum dielectric constant, c is the light velocity in a vacuum and e is the electron charge. The general view of OTR distribution (forward and backforward OTR) is shown in Fig. 1. The OTR patterns for an electron beam with different energy (4 MeV, 20 MeV) and divergence (1 mrad, 10 mrad) are shown in Fig. 2. The OTR peak position is determined by the beam energy and the beam divergence.

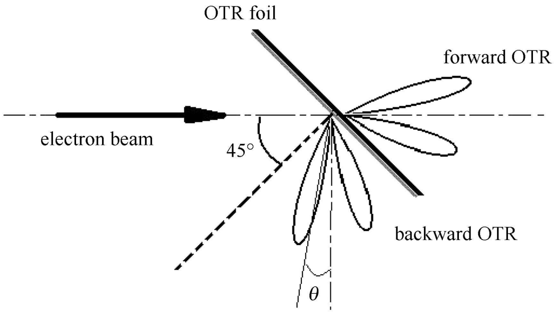


Fig. 1. OTR typical distribution.

When the energy is the same, the larger the divergence value of the beam is, the less sharp the OTR peaks and null become (when the beam divergence is above 30 mrad). For a lower beam energy, the exact form of the theoretical OTR profile and the small angle approximation begin to diverge [4]. So this method is suitable for the higher energy electron beam's divergence.

The expression formula for electron beam normalized emittance is

$$\varepsilon_{\mathrm{n}}=4\cdot\beta\cdot\gamma\cdot\sqrt{\langle x^2\rangle\langle x'^2\rangle-\langle x\cdot x'\rangle^2}, \tag{2}$$

where $\langle\rangle$ expresses the distribution mean function for electrons, β and γ are relativistic factors, x is the projection at the x direction of electrons to the beam center position vector and x' is the projection at the x direction of electrons to the divergence along the beam center axis.

If it is measured at the beam waist for an axisymmetric electron beam, the normalized emittance can be expressed simplified by the following formula

$$\varepsilon_{\mathrm{n}}=4\cdot\beta\cdot\gamma\cdot x_{\mathrm{rms}}\cdot x'_{\mathrm{rms}}, \tag{3}$$

where x_{rms} is the square root value of the beam spot radius and x'_{rms} is the square root value of the beam divergence.

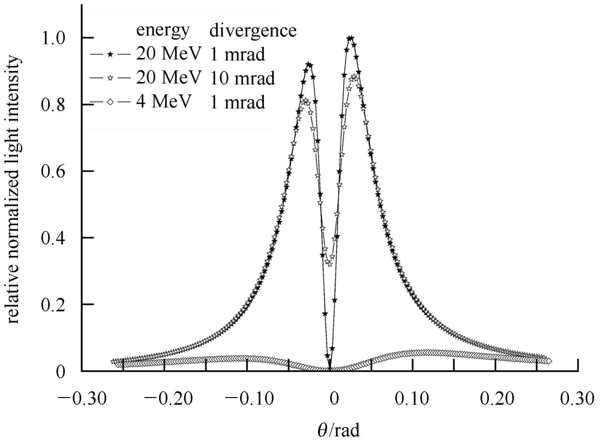


Fig. 2. typical OTR distribution of a 4.5 MeV and a 20 MeV electron beam.

If the beam spot and beam divergence are measured at the beam waist at the same time, the beam emittance at that time can be calculated by the formula (3). If the measurement system works very fast(meaning a very short shutter time), the result obtained is the Instantaneous Emittance at that time.

3 The structure design for the instantaneous emittance measurement system based on OTR principle

The double imaging optical method is a useful way to measure both the beam spot and the divergence at the same time [5]. Fig. 3 is the principle optic arrangement for the double imaging based on OTR. The focal plane imaging method can guarantee that all light with the same incident angle (for example, θ or θ_1) from the OTR target will focus at the same spot (θ' or θ'') on the focal plane. This means that every spot on the focal plane represents the only azimuth angle light beam of OTR. The angular profiles of an OTR pattern on the focal plane is then represented by the image distribution. It is called the infinite distance imaging method. The beam divergence can be calculated ulteriorly from the image distribution on the focal plane [2]. The image plane imaging method can guarantee that all light from the same spot (A or B) on the OTR target will focus at the same spot (A' or B') on the image plane. The spot distribution of an electron beam can be obtained easily in this way; it is called the finite distance imaging method.

The specialty of this imaging method is that the system can image for infinity distance and finity distance at the same time with the same lens.

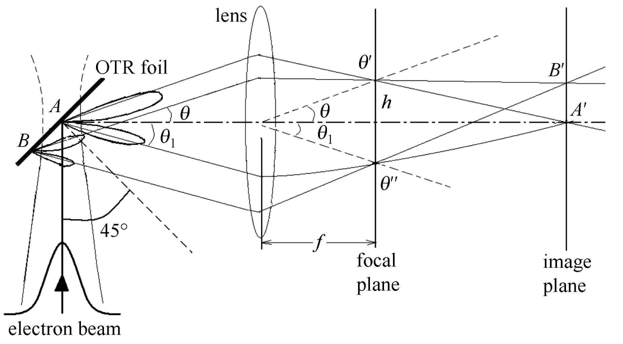


Fig. 3. The optical principle of OTR double-imaging.

Two ICCD cameras with very high speeds must be layed at the focal plane and image plane respectively at same time in order to obtain the instantaneous information about the beam spot and divergence for each shot experiment. ICCD cameras with very short shutter times should be adopted in the system because of the instantaneous measurements demand. An ICCD camera with a shutter time as short as 3 ns is used in the system. Fig. 4 shows the system structure scheme. The ICCD1 is at the focal plane for obtaining the divergence information. The ICCD2 is at the image plane for taking the beam spot image. The controller can produce two trigger pulse GATE1 and GATE2 with the same pulse widths for ICCD1 and ICCD2 at the same time when the system works in the instantaneous mode. These two trigger pulses control two ICCD cameras to open and close at the same time. The information obtained by the two ICCD cameras is time correlated and the instantaneous beam emittance is calculated from the above information.

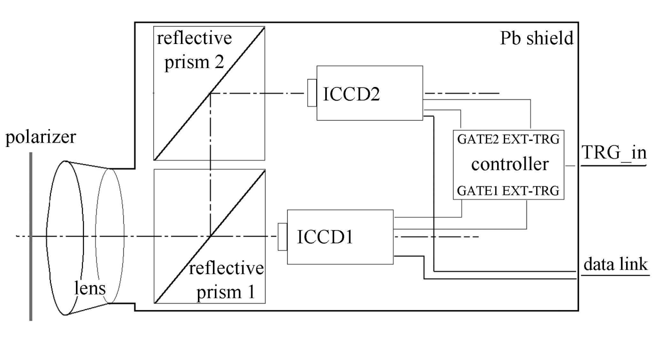


Fig. 4. The structure of OTR double-imaging system.

4 The key parameters design

The imaging lens must meet the focal plane imaging demands and the image plane imaging demands at the same time in the same system. The system design of the lens becomes the key for the whole system. Many factors (Such as the size of the ICCD imaging area, the pixel and the layout of the system) [5] must be taken into the design to reach a suitable measurement precision; the divergence measurement is emphasized when designing the system. The other key principle is that it is much more possible for the system to collect OTR light.

In the focal plane imaging mode, all parallel light rays with an incident angle of θ will focus onto a single point (θ') on the focal plane. The position can be expressed by the image height y on the focal plane [6, 7]

$$h=f\cdot\mathrm{tg}(\theta), \tag{4}$$

where f is the focal length of the lens and θ is the incident angle. In order to accurately compare measured OTR data to theoretically generated patterns, a wide angular range needs to be recorded. An angular range of ±4–±5 OTR peak is a general choice [4]. Obviously, the focal length of the lens is correlative to the beam energy. Fig. 5 shows the relationship between the OTR peak position and the focal length of the lens at different beam energies.

If an electron's energy is about 18–20 MeV and if an ICCD camera with a 25 mm active area is adopted to record the image, an angular range of about 5 times OTR peak position can be collected on the focal plane when the lens focal length is about 200 mm, according to Fig. 5.

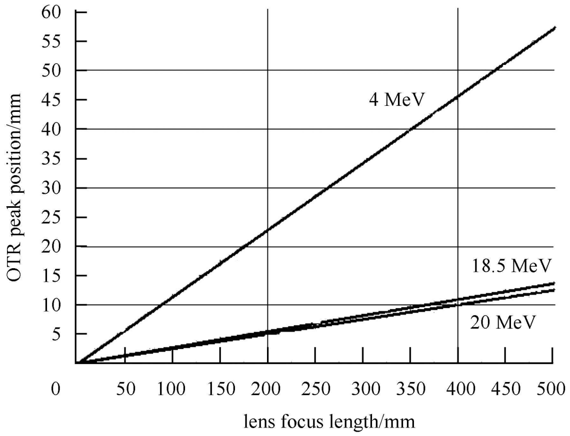


Fig. 5. The OTR peak position vs lens focus length.

Suppose that the radius of the electron beam is r, the object distance of the lens is L under working conditions and the radius of the lens is R. In order to collect the edge light of the beam, the following formula should be met according to Fig. 6.

$$R=r+L\cdot\mathrm{tg}\theta. \tag{5}$$

If θ is replaced by 4–5 times $1/\gamma$ in the above formula, the radius of the lens R can then be calculated. Where $\gamma=E/0.511+1$, E is the beam energy in MeV. The r, $1/\gamma$ are mainly determined by the LIA itself. In order to reduce R, shortening the object distance L is the only way. However, L cannot be absolutely shortened because of the system layout and the limit of imaging. The minimal object distance that can be reached at the field is about 400 mm to 500 mm; the minimal R of the lens is about 57 mm for an electron beam with an energy of 18.5–19 MeV and a radius of about 10 mm. A diameter of about 110 mm is chosen for the lens.

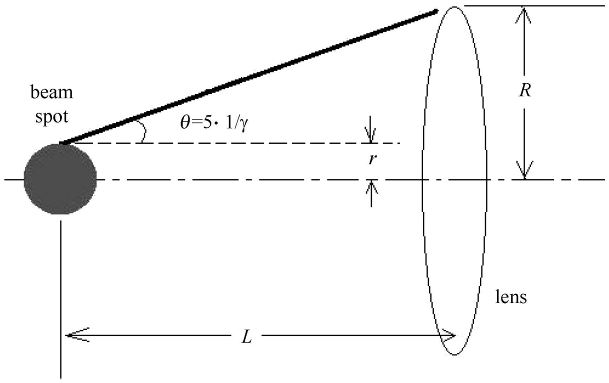


Fig. 6. The methods to calculate the lens.

In the image plane imaging mode, the object distance for the lens is the same as that of the focal plane imaging mode. The minimal L is 400 mm to 500 mm. Suppose that the diameter of the electron beam is about 20 mm, a beam spot image with the diameter of 13.3 mm to 20 mm can be obtained. Enough spatial resolution, such as 10 point/mm, can be reached for beam spot measurement.

5 The electron beam emittance instantaneous measurement experiment

The developed instantaneous measurement system has been adopted in the beam parameters measurement experiment on the Dragon I LIA and a series of results are obtained. Fig. 7 is the experiment layout for Dragon I beam parameter measurement. The distance L between the center of the OTR foil and the lens of the system is 405 mm. The different temporal results are obtained by way of adjusting the delay time τ shown in Fig. 8 in a series of experiments; the time sequence results from the beginning to end of the pulse can be obtained for the electron beam. The stability of the electron beam has been proved to be credible when the experiment conditions are kept the same, so that the time sequence results

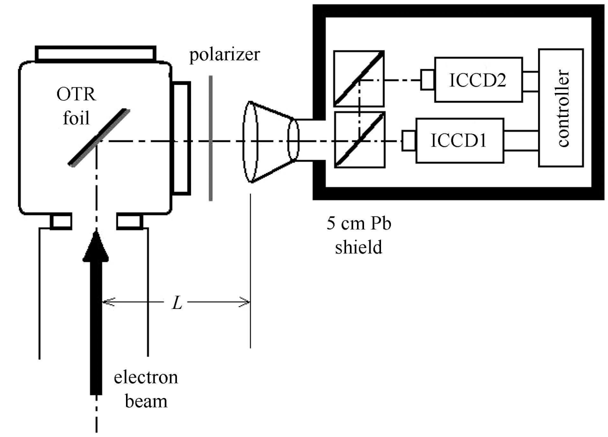


Fig. 7. The experiment layout for Dragon I test.

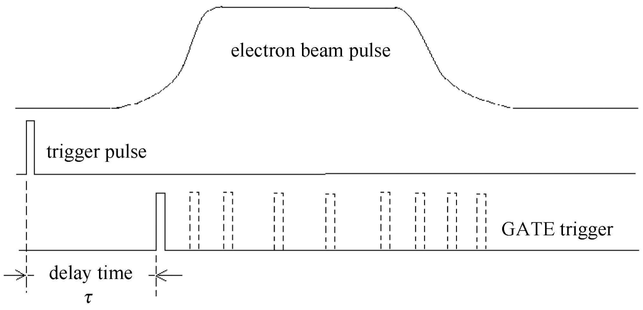
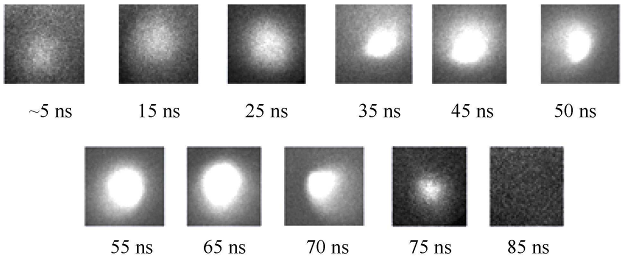
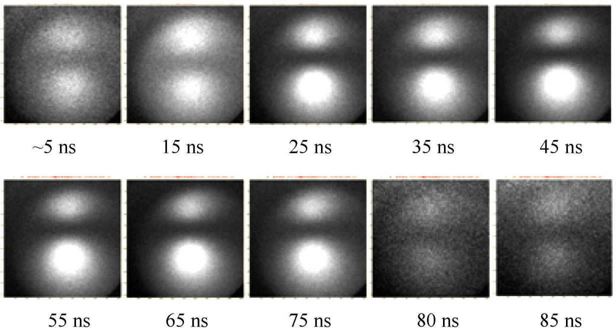


Fig. 8. The delay time and shutter setup.



beam spot

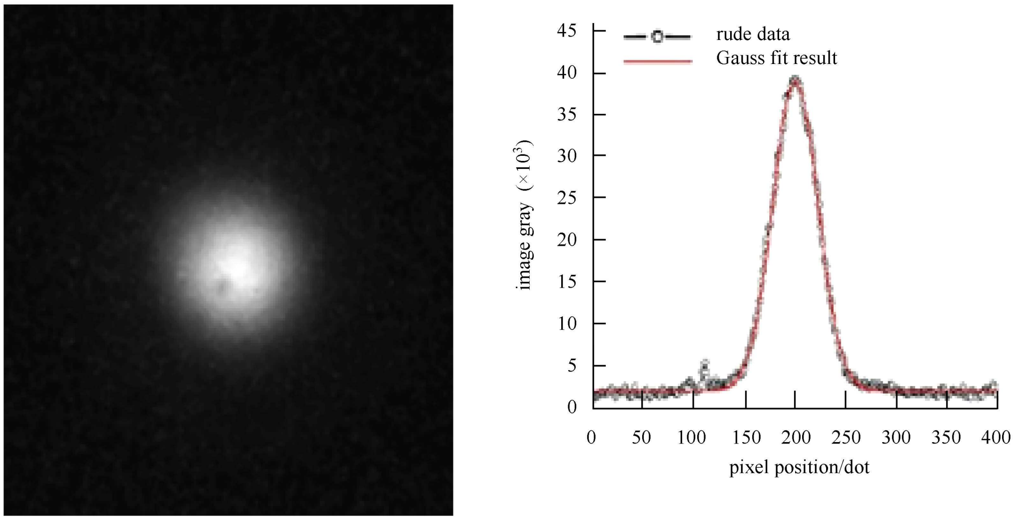


beam divergence

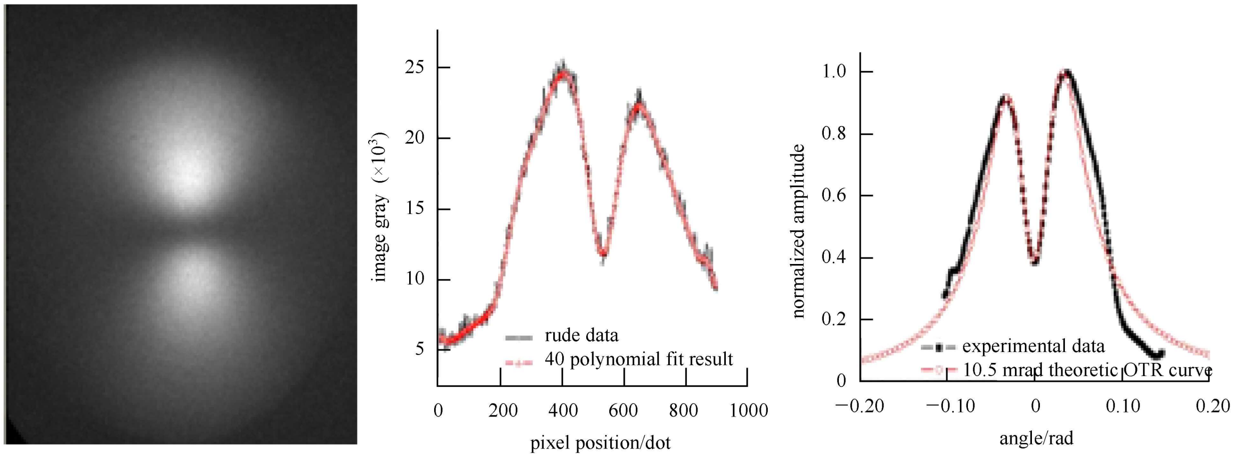
Fig. 9. Beam spot and beam divergence image in sequence captured by the system.

shown in Fig. 9 can be treated as the time-resolved results for the electron beam. The shutter time is set to about 3 ns and the frame interval time is set to 5 ns in these experiments. So the time-resolved ability of the instantaneous measurement system is in fact 5 ns. The highest time-resolved ability of the system is determined by the interval time set in the experiment, so that this ability can reach to a higher level if the interval time is set to a smaller level.

The electron beam parameters have been obtained by this system. Fig. 10 shows the instantaneous beam spot and beam divergence image at one time. The beam spot evidently shows a good Gauss type distribution and the FWHM of the beam spot is about 9.0 mm after Gauss fitting. The beam divergence can be calculated in the following data processing steps. Profile data crossing the middle of the OTR pattern image is fetched out. Polynomial fitting of the data is necessary to reduce the noise in the data. The most matched theoretical OTR curve can be found by way of comparing the polynomial fitted data with the theoretical OTR curves of different divergences and the corresponding divergence of the most matched theoretical OTR curve is the beam divergence. The theoretical OTR curve of 10.5 mrad divergence is the most matched curve with the experimental data shown in Fig. 10.



typical beam spot image and the profile result



typical divergence image and fit results

Fig. 10. The instantaneous beam spot and beam divergence image at one time.

6 Conclusion

The instantaneous electron beam emittance measurement system based on the OTR principle and double imaging optical method can obtain the beam spot and beam divergence simultaneously. The instantaneous beam emittance is then calculated and the result can be treated as the true state of the beam at the test time. The study of this system can help us to deeply understand the principle of the OTR double-imaging method and the design method of the measurement system structure. The instantaneousness of the system is about 3 ns. The system features flexibility and adaptability in applications because the exposure time width and the trigger interval can be independently setup. It could meet the requirements of many measurements for Dragon I LIA.

References

1 JIANG Xiao-Guo, YANG Guo-Jun, ZHANG Kai-Zhi et al. High Energy Physics and Nuclear Physics, 2005, **29**(11): 1095–1099 (in Chinese)

2 JIANG Xiao-Guo, LI Cheng-Gang, WANG Yuan et al. High Energy Physics and Nuclear Physics, 2006, **30**(8): 784–787 (in Chinese)

3 YANG Guo-Jun, LIU Cheng-Jun, LIN Yu-Zheng et al. High Power Laser and Particle Beams, 2004, **16**(9): 1215–1218 (in Chinese)

4 Sage G P Le. Time-Resolved Emittance Characterization of an Induction Linac Beam Using Optical Transition Radiation. UCRL-ID-153254. LLNL, 2002. 11

5 GU An-Jia, DING Yuan-Tao, ZHAO Kui et al. High Energy Physics and Nuclear Physics, 2003, **27**(2): 163–168

6 AN Lian-Sheng, LI Lin, LI Quan-Chen. Applied Optics. Beijing: The Press of Beijing Institute of Technology, 2002, **3**: 36–37

7 HU Yu Xi, AN Lian-Sheng. Applied Optics. Hefei: The Press of China University of Science and Technology, 2002, **2**: 52–53