Precise measurement of the micron-scale spot of ultrashort laser pulse based on film scanning

Fengtie Wu (吴逢铁), Jianrong Zhang (张建荣), Yunbin Chen (陈云彬), and Dongdong Guo (郭东栋)

College of Information Science and Engineering, Huaqiao University, Quanzhou 362021

Received August 8, 2007

A novel and precise micron-scale nanosecond laser spot measurement based on film-scanning method is presented. The method can be used to measure the spot size, beam profile, and intensity distribution of the pulse. The central spot radius of the pulsed Bessel beams with pulse width of 25 ns is measured to be 94.86 ± 5 μm in our experiment through the analysis of the digital image by film scanning, and the result is consistent with the theoretical value of 92.33 μm. Compared with charge-coupled device/complementary metal oxide semiconductor (CCD/CMOS) laser beam profilers, the film-scanning method shows higher measurement accuracy, single shot ultrashort pulse measurable, larger measurable size, and wider measurable wavelength range.

OCIS codes: 140.0140, 120.4630, 320.4240.

The existence of a set of propagation-invariant solutions to the Helmholtz equation was demonstrated in the 1980s[1]. Since then, Bessel, Bessel-Gauss, and newer beams have been studied frequently. The attraction of Bessel beams lies in the fact that theoretically they propagate indefinitely without change of their transverse intensity distribution. Various experiments that made use of Bessel beams have been discussed, covering a wide range of fields including nonlinear optics[2], where the intense central core of the Bessel beams has attracted interest; short pulse non-diffracting fields; atom optics, where the narrow non-diffracting features of the Bessel beams are able to act as atomic guides and atomic confinement devices[3,4]. Special attention was directed to the Bessel beams characteristics including spot size, beam profile, intensity distribution, etc.. We often obtain the data by using charge-coupled device/complementary metal oxide semiconductor (CCD/CMOS) laser beam profilers[5]. However, the short-pulse Bessel beams' tiny concentric annular structure and a micrometer magnitude central spot often fall out of the measurable range of the beam profiler. Conventional high performance laser beam profiler can precisely measure the micrometer continuous wave (CW) laser. In pulse condition, laser beam profiler cannot maintain high resolution or even cannot record pulse at all. To solve this problem, we introduce film-scanning method to measure the ultra-short pulse laser beams. The result appears to be successful and promising.

With the characteristics of real-time, feature-rich and easy-to-use, beam profiler has dominate the beam imaging field today and often seems to be the only instrument to measure laser beam parameters. But the beam profiler brings us convenience as well as shortcomings: part of them can work under pulse condition. The beam profiler whose precision is at 0.1-μm scale can only work under CW condition. The CCD/CMOS devices' noise level[6] and relatively narrow dynamic range will affect the measurement result. The measurable beam diameter is restricted by the size of the imaging sensor area. These problems cannot be fully solved in a short time. Here, the film-scanning method is adopted to overcome these problems.

Silver halide photographic emulsions are well known for several decades to be a perfect tool for imaging applications. There are many different kinds of photographic emulsions to make films for different purposes, such as color negative, black and white (B&W) negative, color reversal, infrared film, He-Ne laser computer tomography (CT) film, and X-ray film. On the other side, film of the same type could have different choices of International Standardization Organization (ISO), grain, dynamic range, and format. The film's area can cover the entire hollow or bottle beam's profile while CCD/CMOS device's imaging sensor size can only cover a small part of it[7]. It is known that image is captured by silver halide as the result of chemical reactions — expose, and the exposed process happens simultaneously as the light reaches the silver halide. Theoretically, the film scanning can be used to catch a single shot pulse with the duration shorter than picosecond.

It is known that the smallest latent image center is composed of three atoms[8]. Theoretically, the pixel in film can reach the size of a molecule. But affected by the silver halide grains size, the pixel size is about nanometer scale[9]. The rolling drum scanner can easily reach the optical resolution of 250000 dpi. It is reasonable to analyze micron-scale laser beam by film-scanning method. CCD/CMOS matrix devices' single photosensitive unit is square micrometer, thus the obtained digital image normally cannot have resolution higher than 3×3 unit square (eg., TaperCamD-WCM20-15 Made by Dataray Company, imaged beam dimension 19.6×14.8 (mm), pixels 14.4 μm^2, best resolution 50 μm). The photosensitive devices used in laser beam profiler are single colored devices. The viewable three-dimensional (3D) color image of the energy distribution is based on pseudo-color transform, interpolation of gray scale and 3D transform. Color film can record gray scale and color simultaneity. Use the same pseudo-color transform system, we can obtain 3D image with more details and sharpness.

Axicon is an optical element which is widely used to generate a series of new type beams[10], and has attracted much attention[11−14]. It focuses an incident plane wave or spherical wave onto the axis, forming a narrow focal line[15]. In the neighborhood of the focal line, the transverse amplitude distribution is nearly a so-call diffraction-free Bessel beam (which allows a small spot propagating along a great distance without spreading). The central region keeps its constant size and intensity.

The field distribution of a Bessel beam propagating along the z-axis is given by

$$\vec{E}(\vec{r},t) = J_0(k_\rho \rho)\exp[-i(\omega t - k_z z)], \tag{1}$$

where J_0 is the zeroth-order Bessel function of the first kind, k_ρ and k_z are the radial and longitudinal components of the wave vector $|k| = 2\pi/\lambda$ (λ is the optical wavelength). $\rho^2 = x^2 + y^2$, $k_\rho^2 + k_z^2 = k^2$, $k_\rho = k\sin\beta$, and $k_z = k\cos\beta$. ρ is the radial distance from the propagation axis and β is the conical angle. If the paraxial approximation (for small base angle of the axicon) is assumed, one can easily get the formula in geometry to calculate the maximum diffraction-free distance $z_{\max}$ and the radius ρ_0 of the central bright spot, using Snell's law which takes the form

$$n\sin\gamma = \sin(\gamma+\beta), \tag{2}$$

where n is the refractive index of the axicon material and γ is the base angle of the axicon (the angle between the conical surface and the flat surface). For small angle approximation, one get

$$\beta \approx \gamma(n-1). \tag{3}$$

Therefore, for a finite radius R of the beam passing the axicon, the maximum diffraction-free range $z_{\max}$ of the Bessel beams is approximately limited by

$$Z_{\max} \approx \frac{k_z}{k_\rho}R = \frac{R}{\mathrm{tg}\beta} = \frac{R}{\gamma(n-1)}, \tag{4}$$

the diffraction-free distance is dependent on the radius R of the beam illuminating on the axicon and the base angle γ of the axicon.

The central spot radius, given in terms of the first irradiance zero, may be written as[16]

$$\rho_0 = \frac{2.405}{k_\rho} = \frac{2.405}{k\sin\beta} = \frac{0.383\lambda}{\gamma(n-1)}. \tag{5}$$

Substituting the parameters $\lambda = 1.064$ μm, $n = 1.516$, $\gamma = 0.5°$, $k = 2\pi/\lambda$ into Eq. (5), we have the Nd:YAG laser Q-switched Bessel beam central spot radius $\rho_0^{\text{theory}} = 92.33$ μm.

The experimental setup used to generate and record the diffraction-free beam is shown in Fig. 1. The part in rectangle is a Q-switched pulsed Nd:YAG laser with anti-resonant ring (ARR) structure[17], which can output high-stability Q-switched or mode-locked pulse laser. Color centered LiF crystal is chosen as the Q-switch element. Collimator convex lenses C_1, C_2 and apertures A_1, A_2 enable the laser to output uniform distribution laser beam with tunable radius. The laser beam passing the axicon forms the J_0 Bessel beam (if the axicon is illuminated by a collimated Gaussian beam, the zeroth-order Bessel-Gauss beam can be obtained). In our experiment, nanosecond pulsed Bessel beam was generated and measured. Figure 2 shows the oscilloscope trace of a single Q-switched pulse with a pulse width (full-width at half-maximum (FWHM)) of 25 ns captured by a fast photodiode and a 400-MHz digitizing oscilloscope (HP54502A).

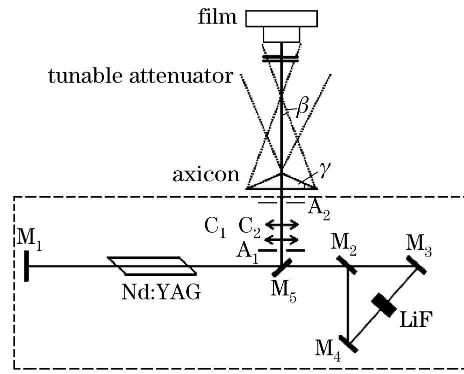

Fig. 1. Experimental setup.

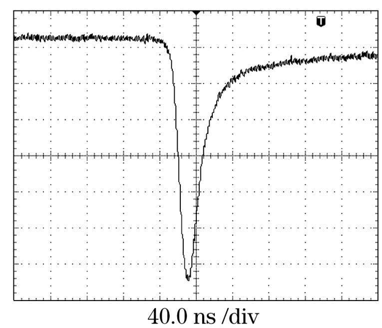

Fig. 2. Oscilloscope photograph of a single Q-switched Bessel pulse.

To measure the pulse intensity profile, both the laser parameter analyzer and film-scanning method were used. Figure 3 shows the two-dimensional (2D) and 3D intensity profiles of output nanosecond pulsed Bessel beams captured by the analyzer (TaperCamD-WCM20-15). It demonstrates that the output pulse is indeed a Bessel beam. However, the resolution of the analyzer limited to give more details of the pulse intensity profile and pattern, such as the ring structure and the size of the central spot radius, since the nanosecond Bessel pulse is with a short duration and the central spot radius of the pulse is only several tens of micrometers. To better understand the relative parameters of the pulse, we adopt a novel and precise method — film scanning.

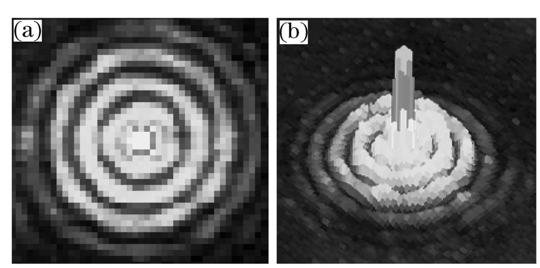

Fig. 3. (a) 2D and (b) 3D beam profiles captured by the laser parameter analyzer.

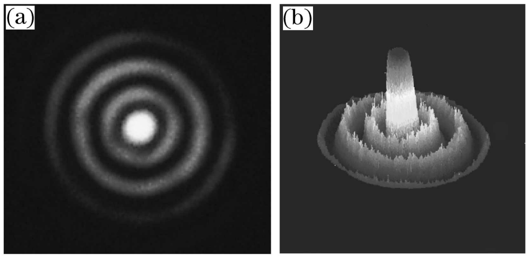

Fig. 4. (a) 2D and (b) 3D beam profiles captured by the film-scanning method.

Fujifilm RVP100F used in the experiment is a kind of easy-scanning color reversal film with ultra-fine grain and high contrast. Short-pulse laser directly exposed on the color reversal film. The film was scanned by the rotating drum image scanner (Chroma Graph 330, Linotype-Hell Company). The 40× magnified digital color image was then obtained. Figure 4 shows the intensity profiles of the Bessel pulse captured by the film-scanning method with the same experimental condition for laser parameter analyzer. A 3D image of energy distribution is also shown based on pseudo-color transform. Therefore, we can obtain the fine structure of the intensity pattern which gives us more information about the spot and allows us to measure the central core spot size of the Bessel pulse which cannot be satisfactorily measured by the advanced beam profiler TaperCamD-WCM20-15. Using the ratio expression

$$\rho^{\mathrm{mag}}/d^{\mathrm{mag}} = \rho^{\mathrm{real}}/d^{\mathrm{film}},$$

where ρ^{mag} is the central spot radius in digital magnified image, ρ^{real} is the real central spot radius, d^{mag} is the feature spots distance in digitial magnified image, d^{film} is the feature spots distance in film, and the real central spot radius of Bessel beam was finally measured as $\rho_0^{\mathrm{exp}} = 94.86 \pm 5$ μm. The error of ± 5 μm comes from the edge judgement. From the digital magnified image we will find the distance between the positions with maximal and minimal intensities is 10 μm. The central spot in Fig. 4 is sharp while the counterpart in Fig. 3 is blurry.

A detailed precise ultra-short pulse laser spot measurement method based on film scanning has been presented. Compared with the laser beam profiler, the film-scanning method has been proved to be a low-cost and easy way to measure one single shot ultra-short laser pulse intensity distribution with larger measurable area and higher resolution. Choosing suitable film, this method can work on ultraviolet (UV) wavelength as well. It is promising to use this way to measure picosecond, femtosecond or shorter laser pulse with tiny complex intensity distribution. Recently, this method has been successfully used in measurement of micron-scale spot of nanosecond pulsed Bessel-Gauss beams[18]. Additionally, the measurement and analysis of micron-scale size of picosecond pulsed Bessel beams are under way.

This work was supported by the National Natural Science Foundation of China (No. 60477041) and the Natural Science Foundation of Fujian Province, P. R. China (No. A0710011 and A0410017). F. Wu's e-mail address is ftwu@public.qz.fj.cn.

References

1. J. Durnin, J. Opt. Soc. Am. A **4,** 651 (1987).
2. T. Manz, U. T. Schwarz, and M. Maier, Opt. Commun. **235,** 201 (2004).
3. J. Arlt, K. Dholakia, J. Soneson, and E. M. Wright, Phys. Rev. A **63,** 063602 (2001).
4. D. G. Grier, Nature **424,** 810 (2003).
5. X. Zhou, D. Cao, and Y. Wu, Opt. Instrum. (in Chinese) **263,** 38 (2004).
6. Y. Cao and C. Gao, Opt. Technique (in Chinese) **305,** 583 (2004).
7. M.-D. Wei, W.-L. Shiao, and Y.-T. Lin, Opt. Commun. **248,** 7 (2005).
8. T. Tani, Photographic Science and Photochemistry (in Chinese) **19,** 48 (2001).
9. S. Fu, J. Yue, and S. Liu, Photosensitive Materials (in Chinese) (3) 14 (1997).
10. Y. Qian and Y. Wang, Chin. Opt. Lett. **2,** 232 (2004).
11. F. Wu, Y. Chen, D. Guo, and J. Zhang, Chin. J. Lasers (in Chinese) **34,** 1073 (2007).
12. F. Wu and X. Zheng, Acta Opt. Sin. (in Chinese) **28,** 174 (2008).
13. F. Wu, D. Guo, Y. Chen, and Z. Qiu, Opt. Precision Eng. (in Chinese) **15,** 1692 (2007).
14. X. Jiang, F. Wu, and B. Liu, Chin. J. Lasers (in Chinese) **34,** 1538 (2007).
15. M. Dong and J. Pu, Opt. Laser Technol. **39,** 1258 (2007).
16. J. Arlt, K. Dholakia, L. Allen, and M. J. Padget, Phys. Rev. A **60,** 2438 (1999).
17. F.-T. Wu and W.-Z. Zhang, Opt. Laser Technol. **32,** 107 (2000).
18. F. Wu, Y. Chen, and D. Guo, Appl. Opt. **46,** 4943 (2007).