

Knife-edge scanning measurements of subwavelength focused light beams

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This note describes a convenient working technique for measuring the minimum size focused spot formed by a lens system. The technique is routinely capable of measurement precision of better than $\frac{1}{8}\lambda$. The theory of knife-edge scanning is presented, and the relationship of the measured spot profile to the actual spot profile is shown to be relatively insensitive to the acceptance solid angle of the photodetector. Finally, some typical results of high resolution microscope objectives are presented.

I. Introduction

This paper describes a convenient working technique for measuring the minimum focused spot formed by a lens system. This measurement is of importance for at least two reasons: (1) the size and structure of the smallest spot are one measure of the quality of an optical system¹—the point spread function—and (2) in a number of optical applications, such as for example optical recording systems,² one important system parameter is the size of the smallest possible focused spot. For spot diameters less than $1\text{ }\mu\text{m}$ such measurements can be difficult and unreliable. The technique to be described is routinely capable of measurement precision better than $500\text{ }\text{\AA}$. In the following paper we first review other methods for spot size measurements, then discuss some pertinent theoretical properties of knife-edge scanning and the techniques and advantages of our particular implementation, and finally present some typical results of our measurements.

In addition to knife-edge scanning there are two other techniques for spot size measurement: (1) optical imaging of the focused spot and (2) a computational determination based upon interferometric measurement of the far field pattern.³ The first method is basically to view the focused light spot with a microscope. The magnified image of the spot is then displayed and measured photoelectrically. This method is quick and has the advantage that it displays the entire 2-D focused spot. It has two serious disadvantages. First it is predicated upon the quality of the magnifying microscope. Indeed the spot size that is measured is in reality the spot to be measured convoluted with the point spread function of the magnifying microscope for an incoherent system. While for a coherent system it is the transform of the product of the transforms of the point

spread function of the spot to be measured and the point spread function of the magnifying microscope. Thus this technique is suitable for measurements of low numerical aperture systems since high quality, higher numerical aperture microscope lenses are available and can be used. A second disadvantage of this technique is that there is no *in situ* calibration. Calibration must be performed by measuring some object of known size which is comparable to the focused spot to be measured. The other method, a computational measurement based upon interferometric measurements of the far field of the light spot, is difficult, requires considerable equipment, and is an indirect measurement.

Spot measurement by knife-edge scanning, however, is simple, accurate, and direct. There have been a number of references in the literature to knife-edge scanning techniques.⁴⁻⁷ As described, however, none of these implementations of the knife-edge scanning method are directly and simply applicable to the measurement of submicron spot sizes due to the inaccuracies in determining the knife-edge location. Our technique basically consists of measuring the power not occluded by a knife-edge scanning through the focused spot while simultaneously measuring the displacements of the knife-edge interferometrically. The interferometer is a simple optical configuration which is easily aligned and inexpensively constructed. The knife-edge scan is done repetitively many times per second in order to eliminate problems of mechanical, electrical, and optical drifts.

II. Theory

One advantage of the knife-edge scanning method which has not been explicitly recognized is that the basic accuracy of the measurement is relatively insensitive to the acceptance angle of the photodetector. Even if the photodetector does not completely capture the light from the focused spot the accuracy of the measurement of the spot width is only slightly compromised. This is particularly important when measuring submicron

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spot sizes which already are formed by high numerical aperture beams. That the addition of further losses of the light by the knife-edge diffraction, by geometric aperturing, by Fresnel reflection of high angle incidence light on the detector, etc. does not substantially affect the measurement is very significant. It is clear that if the photodetector captures all the unoccluded light, the true spot profile can be obtained by differentiating the photodetected signal as a function of the knife-edge position. We first show how the measurement of the spot size is affected in the other limit when the photodetector captures only the axial light and then present the results of the calculations when the acceptance solid angle of the photodetector is such that some but not all the light is detected.

Let us consider first the case of a 1-D spot being scanned by a knife-edge with the photodetector collecting only the axial light. The light has an amplitude profile $A(x)$. The functional form of the knife-edge occluding half of the plane can be represented by

$$E(x) = \frac{1}{2}[1 + \text{sgn}(x)], \quad (1)$$

where

$$\text{sgn}(x) = \begin{cases} +1 & x > 0, \\ -1 & x < 0. \end{cases}$$

The angular spectrum⁸ of the light spot occluded by the knife-edge is then the Fourier transform of the spot profile convoluted with the Fourier transform of the moving knife-edge, that is, the angular spectrum $p(K, \Delta)$ is given by

$$p(K, \Delta) = a(k) \otimes e(K) \exp(iK\Delta), \quad (2)$$

where

$$a(K) = \int_{-\infty}^{\infty} A(x) \exp(-iKx) dx, \\ e(K) = \frac{1}{2}\delta(K) + \frac{1}{iK},$$

and Δ is the location of the knife-edge. The axial photodetected signal is then $|p(0, \Delta)|^2$, and the measured spot profile will then be $S(x)$ where

$$S(x) = \frac{d}{d\Delta} |p(0, \Delta)|^2_{\Delta=x}. \quad (3)$$

This results in

$$S(x) \propto A(x) \int_x^{\infty} A(u) du. \quad (4)$$

Equation (4) states that if only the axial light is collected, the measured spot profile is somewhat asymmetric, with the peak of the spot shifted to one side of the optical axis. However, the width of the spot is not greatly modified. Assuming $A(x)$ is a Gaussian spot profile, the measured full width at half-maximum is ~15% larger than the true full width at half-maximum intensity.

When the acceptance solid angle of the photodetector is such that some but not all the light is detected, an analytic solution to the measured spot profile is not

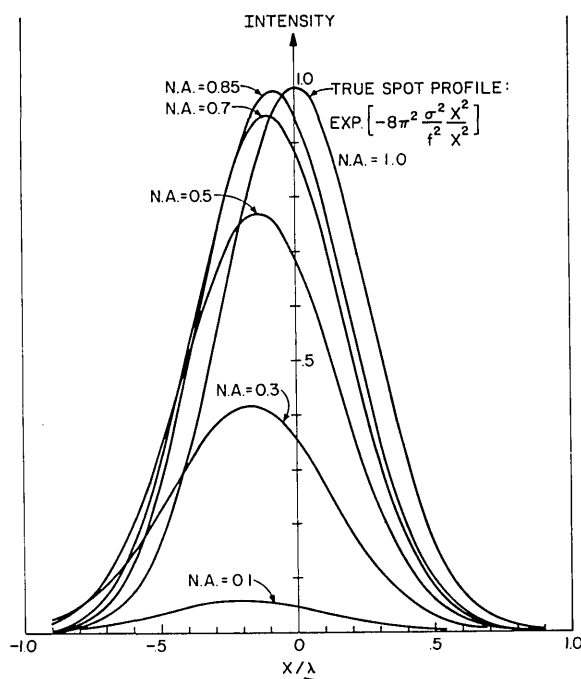


Fig. 1. Computed spot profiles for various acceptance numerical apertures (N.A.). The illumination wavefront has the intensity profile $\exp(-r^2/2\sigma^2)$ at the front focal plane with $\sigma = 0.3f$, f being the focal length and r the radial distance from the optical axis. The intensity scale is normalized by assuming the peak intensity of the N.A. = 1.0 case to be 1. $x = 0$ is the optical axis.

instructive. We have numerically computed the effects of the finite acceptance solid angle for a Gaussian spot profile of 0.9 numerical aperture. These results are presented in Fig. 1 for various acceptance solid angles, as measured by an effective numerical aperture, were taken to be square with one side parallel to the knife-edge rather than the more typically round. The spot profiles are obtained by differentiating the collected light intensity as a function of the knife-edge position. Note that for an acceptance numerical aperture approximately one-third of the true spot numerical aperture (N.A. = 0.3), the measured width of the spot profile is only about 10% larger than the true width. For the case of an acceptance numerical aperture = 0.85, the measured width is practically identical to the true width.

III. Description of the System

The system consists of two subsystems: (a) the scanning knife-edge/photodetector system and (b) an interferometer which provides a metric for the knife-edge displacements. A diagram of this system is shown in Fig. 2.

A. Knife-Edge/Photodetector Scanning System

The scanning knife-edge/photodetector subsystem consists of (1) a knife-edge, (2) a scanning system, and (3) a photodetector with associated electronic amplifi-

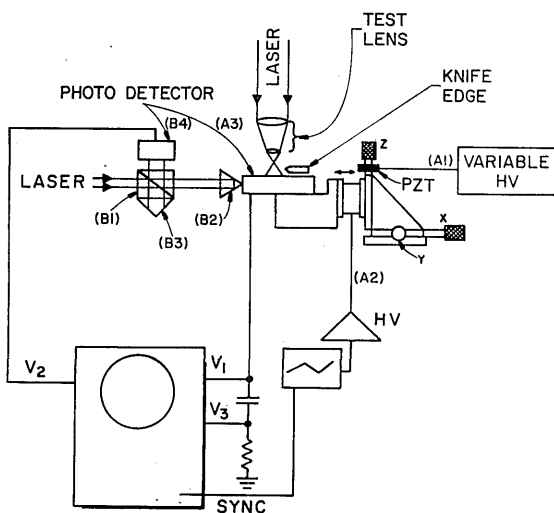


Fig. 2. Schematic diagram of the knife-edge scanning apparatus.

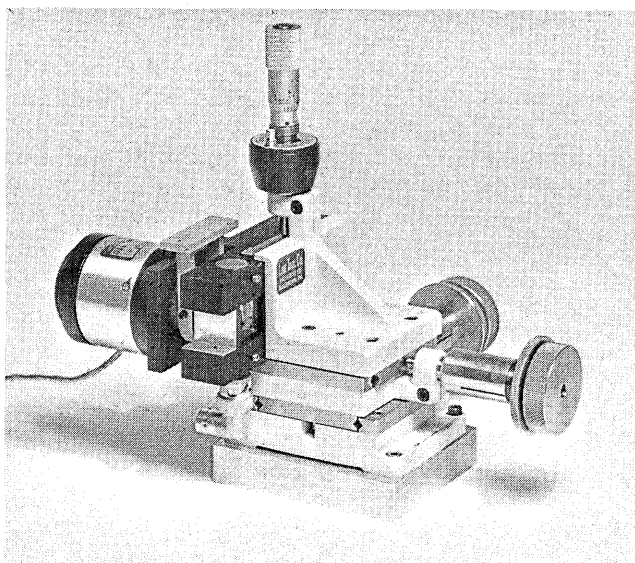


Fig. 3. Photograph of the integrated scanner-interferometer stage mounted on its xyz stage.

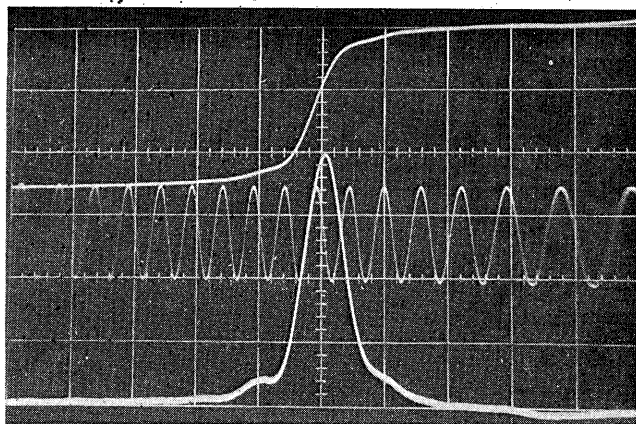


Fig. 4. Oscilloscope photograph of the measurement of a submicron focused spot (lens—Leitz F1 100, N.A. = 0.95, $\lambda = 4416 \text{ \AA}$).

ers. The knife-edge is the most critical element. It must be smooth on the scale of the focused spot dimensions. We have found that a nick-free region of a razor blade, a cleaved gallium-arsenide 60° knife-edge, or a smooth straight pattern edge on a chromium on-glass integrated circuit photomask are satisfactory. To scan the knife-edge we have used both commercial PZT or electromechanical laser mirror translators. The motion transducer is mounted on an xyz translation stage having both conventional and differential screw adjustments on the two horizontal axes. The knife-edge scanner transducer moves horizontally and is driven by a triangular waveform generator. The vertical motion is used for focusing. Here we use a commercial PZT/micrometer unit with a variable high voltage supply to drive this PZT element for the very fine motions needed for critical focusing. Recall that the depth of field of a $3000\text{-\AA}$ spot is only about $1000 \text{ \AA}$. It has been our experience that both manual scans and manual fine-focus adjustments using differential screws are unreliable and unreproducible over the small dimensions of interest here. The photodetector used is a 1-cm diam P-I-N photodiode used in a reverse-biased mode. The knife-edge is placed directly upon the glass window of the detector so that the light acceptance solid angle is maximized. Nonetheless we probably do not collect all the light when measuring spots formed by high numerical aperture lenses. In order to collect all the light from a lens of N.A. = 0.95, a 1-cm diam detector can be no further than 1.6 mm from the plane of focus. Sufficient amplification is usually available with the input amplifier of an oscilloscope.

B. Interferometer

The purpose of the interferometer is to provide a metric for the displacements of the knife-edge scanning system. We have found that the motion of most translators is not uniform. There exists a transient when the velocity reverses, and on some translators the motion between reversals is also not perfectly uniform. The interferometer is a conventional one consisting of (1) a beam splitter cube, (2) a corner cube mounted on the scanning translator, (3) another corner cube optically contacted with a drop of immersion oil to the beam splitter cube, and (4) a P-I-N photodiode to detect the fringes electrically. The components themselves are not highly precise and are relatively inexpensive. Since the interferometer is used solely to provide a real time metric, high fringe contrast is not necessary; it is only necessary that the fringes be photoelectrically detectable.

An actual photograph of the instrument is shown in Fig. 3. It is compact and rugged and accordingly very stable. Nonetheless we generally mount and use it on a vibration-free, stable table. The most convenient mode of device operation is to scan the knife-edge periodically and to display the knife-edge signal, its derivative, and the interferometer signal simultaneously on an oscilloscope. The triangular waveform generator is typically set at 3.5 Hz. This generator also supplies a synchronizing pulse to the oscilloscope. By using the oscilloscope in the delayed time base mode we can

Table I. Measurements of Microscope Objectives

		Half-intensity width	
		$\text{\AA}$	λ
Lenses tested at 4416 $\text{\AA}$			
B&L	$\times 20/0.4$	8300	1.9
B&L	$\times 43/0.65$	5500	1.25
Leitz	$\times 50/0.85$	4700	1.1
Zeiss	$\times 80/0.95$	3600	0.82
Leitz	$\times 100/0.95^a$	3300	0.75
Leitz	$\times 100/0.95^b$	3100	0.70
Leitz	$\times 100/0.95^c$	2900	0.66
Leitz	$\times 160/1.4^d$	1600	
Lenses tested at 6328 $\text{\AA}$			
Leitz	$\times 50/0.85$	5700	0.9
Leitz	$\times 100/0.95$	4400	0.7
Lenses tested at 8200 $\text{\AA}$			
Edmund	$\times 20/0.4$	17,000	2.1
Beck	$\times 40/0.65$	10,300	1.25
Leitz	$\times 50/0.85$	6,400	0.78

^{a,b,c} Different individual lenses of the same manufacturer's lens type.

^d Oil immersion lens.

conveniently examine and expand only that portion of the knife-edge scan which contains the transition across the focused spot. Since the display is real-time and repetitive, the effects of various lens adjustments on the focused spot size can be observed directly and the smallest focused spot diameter quickly determined.

Figure 4 is a typical photograph of the oscilloscope trace with the system in operation. The uppermost trace is the knife-edge scan signal (V1), the middle trace is the interferometer signal (V2), and the lower most trace is the derivative of the knife-edge scan signal (V3) which is our measured spot profile. Each complete cycle of the interferometer signal represents a dis-

placement of one-half wavelength. Thus the spot size displayed has an intensity half-width on the order of 0.75λ ($\lambda = 4416\text{\AA}$) or $\sim 3300\text{\AA}$, where the accuracy of the measurement is only limited by how well one can interpolate between the peaks of the interferometer signal. It is clear from Fig. 4 that a precision of $1/8\lambda$ (which corresponds to one quarter of a cycle of the interferometer signal) or better is routinely accessible. Table I lists several additional lens measurements that we have made using this technique. It should be noted that measurements of oil immersion objectives are possible with this technique, and one such measurement is reported in Table I.

In conclusion we have described a knife-edge scanning technique for measuring focused spot profiles which is simple, direct, and routinely capable of measurement precision of better than $1/8\lambda$. By using an interferometer to measure the displacements of the knife-edge the system becomes absolutely calibrated at each and every scan. We have further shown the theoretical basis for this method and pointed out the relationship between the true value and the measured value of spot width and its dependence upon the acceptance solid angle of the photodetector. Finally we have presented some typical results obtained on measurements of various high resolution microscope objectives.

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NSB Professional Staff Established

The National Science Board (NSB) has established its first professional staff to provide full-time support on Board-related matters. Dr. C. E. Sunderlin is named Head of the NSB Scientific Support Staff and will serve as Executive Secretary and Staff Director of the NSB Committee on the Tenth NSB Report. Dr. Robert Wright serves as Executive Secretary and Staff Director, Committee on the Ninth NSB Report; and Dr. James Zwolenik as Executive Secretary of the Planning and Policy Committee and Executive Secretary of the Committee on Mechanisms for Improved Policy Formulation and External Communications. Miss Vernice Anderson serves as Head of the NSB Operations Staff and Executive Secretary of NSB.