# Laser Beam Propagation Ratio Parameters, Traceable to National Measurement Standards

S R G Hall [a] , S D Knox [a] , D Robinson [b], H Yang [b], A M Scott [c], S C Woods [c], A J Turner [c] and A Lewin[c]

[a] National Physical Laboratory, Teddington, Middlesex, UK, TW11 0LW;

[b] Arden Photonics Ltd, iBIC, Holt Court South, Jennens Road, Aston Science Park, Birmingham, B7 4EJ, UK;

[c] QinetiQ, Optronics Research & Consulting, Optronics Centre, Malvern Technology Centre, St Andrews Road, Great Malvern,WR14 3PS, UK

**Abstract**

This paper reports the establishment of an infrastructure suitable for underpinning traceable calibration of beam propagation parameter measurement instrumentation and the development of suitable measurement techniques. The accurate knowledge of the $M^2$ parameter is required for a diverse range of applications including semiconductor manufacture, process control, laser machining, thin-film transistors (TFT), fundamental research into frequency doubling, and the production and characterisation of optical components. Characterisation of the size and position of the beam waist is essential for the correct hazard classification of extended source laser systems using the IEC 60825 series of standards. A system for measuring beam propagation factor measurement has been developed at NPL based on the methodology outlined in the ISO 11146 series of standards. This methodology uses spatial intensity profile measurements of the beam at defined points along the direction of propagation of the beam through a beam waist produced by a convex lens. The beam widths obtained using a CCD and a converging second moment method, are fitted to a hyperbolic propagation envelope and the beam propagation coefficients are obtained from the fitted curve. The traceability of this method has been provided by using graticules calibrated against length standards and carefully measured CCD camera parameters.

## 1. Introduction

Measurement of the propagation characteristics of laser beams enables the effective prediction of optical system parameters, removing the reliance on “trial and error” to accomplish the requisite performance. A number of commercially available beam propagation measurement systems display results to three significant figures for beam parameters, implying a 1% uncertainty that is not necessarily reflected in practice.

Through consultation with industry, a need for traceability for these devices was established. This requirement has been met by development of a reference measurement system, which uses the National Physical Laboratory (NPL) primary length standards to provide traceability for beam propagation parameters, and uses the accepted methodology described in the ISO 11146 series of standards. [1][2][3]

## 2. Beam measurement methods

Measurement of the optical constants of the propagation envelope of a beam [4][5] has been the subject of considerable research over the last 14 years. A consequence of this work is the evolution of ISO standards for the measurement of the diameter and divergence of a beam ISO 11146:1999 “Test methods for laser beam parameters: beam widths, divergence angle and beam propagation factor” [1].

There are a number of methods available for measurement of the diameter of a beam as well as its far-field divergence. The basic principles for those methods have been established in an ISO standard[1][3]. They are applicable to laser beams with a relatively small beam propagation ratio, $M^2$. Recent research has demonstrated that adequate steps have to be taken to counter the effects of noise and offset errors when measuring the transverse irradiance distribution of a beam. When these steps are taken, the propagation behaviour of incoherent broadband beams as well as high-quality laser beams can be predicted reproducibly with considerable precision.[3][4][6]

## 3. Description of the reference system and calibration

The system layout is deliberately kept as simple as possible to reduce stray light effects and aberrations caused by optical elements (see fig 1). The CCD camera is mounted on an adjustable stage with sufficient degrees of freedom to allow the system to be setup to be collinear with the beam propagation direction. This stage is mounted on a stepper motor driven slide controlled by the measurement system software. An optical encoder is used to allow relative measurement of translation in the beam propagation direction. To ensure accuracy in the determination of the beam width the CCD array in combination with the analysis software is calibrated using a photoetched transparent graticule with traceable calibration.

To provide accurate determination of the position of the beam waist the stepper motor driven stage fitted with an optical encoder is calibrated against a length measuring interferometer, resulting in a positional accuracy of ±0.01 mm.

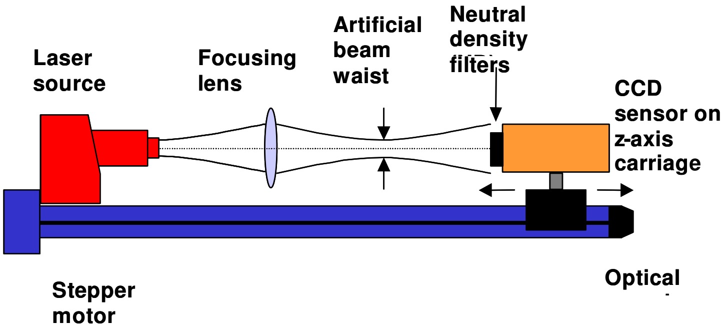


**Figure 1.** $M^2$ System layout.

After background subtraction, the corrected image is processed using the convergent second moment (CSM) method, which progressively limits the dimensions of the CCD window without clipping the beam intensity profile. This reduces the noise contribution to the second moment evaluation. The vertical and horizontal CSM values of the beam incident on the NPL CCD array are calculated. A cross-moment of the beam distribution in the converged window is used to calculate the azimuth of the principal axes of potentially non-circular distributions. NPL software then outputs the final 2$^{nd}$ moment measurements in the X and Y axes.

## 4. Measurements made using the system

Initial measurements were made using a laser source conditioned to provide a near $TEM_{00}$ Gaussian beam. This source was a flashlamp pumped yttrium lithium fluoride (YLF) laser that had been fibre coupled and then collimated to provide the test beam. The measured $M^2$ ratio using our ISO compliant system was 1.06.

To explore the linearity of the system with respect to higher $M^2$ values a stable laser source within this range was required. The optimal method to achieve this was through the use of a variable $M^2$ source. This is achieved using a Vertical Cavity Surface Emitting Laser (VCSEL) that changes $M^2$ in response to variation of its current supply in a repeatable manner. The VCSEL variable $M^2$ source was used to test a prototype commercial $M^2$ system [7][8] against the NPL reference $M^2$ system. This has allowed for further improvement of the prototype device by the manufacturer. Care is required to ensure enough data is collected to remove ambiguity in far field divergence and beam waist determination.[9] (see fig 2).

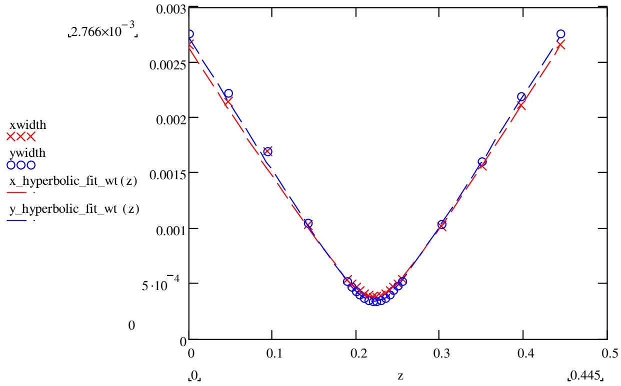


**Figure 2.** Hyperbolic plot giving an $M^2$ of 3.46 achieved using a VCSEL.

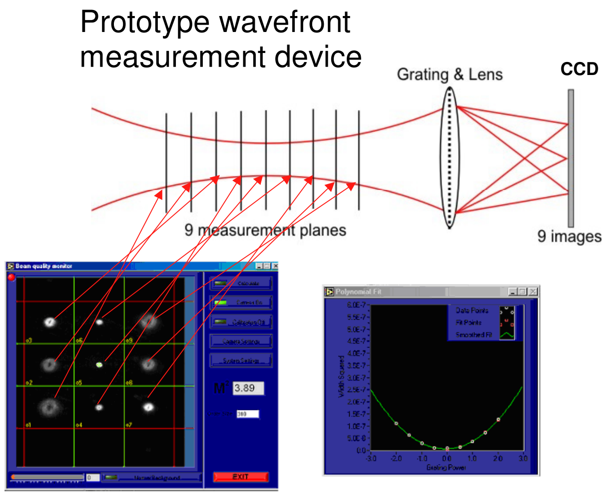


**Figure 3.** Prototype wavefront sensor utilising a multiple distorted diffraction grating

An improved prototype meter (see fig 3) will be compared with the NPL system (fig 4) by utilizing the demonstrated stability of the VCSEL source to allow substitution measurements.[10]

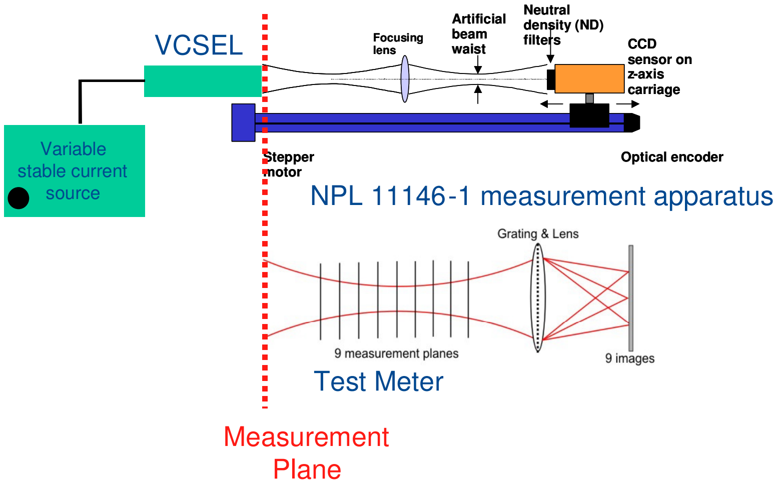


**Figure 4.** Comparative measurement of test meter vs. NPL ISO 11146 system.

## 5. Conclusion

We have outlined a traceable approach to allow calibration of beam propagation ratio measurement devices. The use of a variable $M^2$ source has allowed improved linearity calibration of test meters by comparison with the ISO method. This compares favourably to the reliance on interpolation between discrete $M^2$ measurements made with a range of laser sources. The utility of the system will be demonstrated using results presented at the conference of calibration of a recently improved prototype commercial device.


## 6. Acknowledgment

This work was carried out under the National Measurement System, Photonics programme.


## 7. References


[1] EN ISO 11146-1:2005 Lasers and laser-related equipment – Test methods for laser beam parameters – Beam widths divergence angle and beam propagation factor

[2] EN ISO 11146-2:2005 Lasers and laser-related equipment Test methods for laser beam widths divergence angles and beam propagation ratios General astigmatic beams

[3] PD ISO/TR 11146-3:2004 Lasers and laser-related equipment Test methods for laser beam widths divergence angles and beam propagation ratios Intrinsic and geometrical laser beam classification propagation and details of test methods

[4] Amarande S Giesen A and Hügel H 2000 Propagation analysis of self-convergent beam width and characterization of hard-edge diffracted beams *App Optics* **39** No 22

[5] Siegman A E 1993 Defining measuring and optimizing laser beam quality *Proc SPIE Laser Resonators and Coherent Optics: Modeling Technology and Applications* **1868** (Los Angeles, CA:SPIE)

[6] Hall S, Ward B, Crane L and Gibbs D 2005 Investigation of a measurement technique to determine the apparent source size for light emitting diodes HSE Books research report 345 Web version only ISBN 0 7176 6108 3

[7] Blanchard P M and Greenaway A H 1999 Simultaneous multiplane imaging with a distorted diffraction grating *Applied Optics* **38**(32) pp 6692-6699

[8] Scott A M and Woods S C 2002 Single Shot Measurement of Laser Beam Quality Parameter M2 *Proc.SPIE Symposium on beam measurement* (Boulder, CO: SPIE)

[9] Johnston Jr T F 1998 Beam propagation (M2) measurement made as easy as it gets: the four-cuts method *Applied Optics* **37** Issue 21 pp 4840-4850

[10] Hall S R G, Robinson D, Knox S D, Yang H, Scott A M, Woods S C, A J Turner and Lewin A 2007 Improvement and Commissioning of a Novel Technology for the Measurement of Laser Beam Profiles *Proc.SPIE Photonics West, Laser Resonators and Beam Control IX conference* (San Jose, CA: SPIE)