Numerical Aperture measurement with HASO and LIFT wavefront sensors

Imagine Optic, 18 rue Charles de Gaulle, 91400 Orsay, France
contact@imagine-optic.com

APPLICATION NOTE

Summary

As optics and components become smaller and smaller, controlling their quality and physical characteristics becomes more challenging. For laser beams, one important characteristics of their design is their numerical aperture (NA) which describes how strongly the beam focuses or spreads during its propagation. Brilliance RGB has developed the world's smallest miniature RGB laserchip to date, Neptune, which is based on photonic integrated circuits (PICs) with silicon nitride waveguides. Neptune combines high brightness and ultra-compactness (0.024 cc, weight 50 mg). These two characteristics make it ideal for wearable display technologies, AR and VR technologies. Nonetheless, it makes it complicated or time-consuming to test with classical methods, as the key feature relies on measuring the NA of the laserchip at three different wavelengths (red: 640 nm, green: 520 nm, blue: 450 nm)

In this Application Note, we'll present how a wavefront sensor and the combined measurement of phase and intensity allows to solve classic test bench limitations and easily measure the numerical aperture of a laser beam.

Brilliance RGB, a manufacturer of laserchips for projection applications, has developed the world's smallest miniature RGB laserchip, Neptune. This bright and compact source is perfectly suited to Augmented Reality (AR) applications. Its key features are introduced in Figure 1 below.

BRILLIANCE

Model: Neptune laserchip

Three combined RGB wavelengths: 450, 520, 640 nm

Numerical aperture: 0.04 to 0.07

Dimensions: 4.17 x 3.95 x 1.5 mm

Figure 1. Key features of Neptune laserchip

Since the laser emits at different wavelengths, both the absolute Numerical Aperture (NA) values and their relative consistency are critical for the manufacturer. Indeed, consistent NA values among the different wavelengths eliminate the need for wavelength-specific optics and simplifies the system, its alignment, and its overall size.

The NA defines how wide the cone of light emitted by a source is. In the case of Neptune, the output beam comes from a silicon nitrite waveguide that is implemented directly on the laserchip. A way to calculate the numerical aperture of the output beam is by using the formula:

$$NA = n\,.\sin(\theta)$$

Where n is the refractive index of the propagation medium and θ the maximum half-angle produced by the beam.

Traditional methods

Classical methods and benches for the measurement of Numerical Aperture usually require a beam profiler. Several techniques are available.

One common technique is the Focal plane/Fourier plane method [1]. Experimentally, a lens of known focal distance f is placed in front of the beam profiler and images the focal plane (back-focal). In the focal plane a ray r from angle θ is imaged to a transverse position $r = f.\tan(\theta_r)$. The radial extent r_{max} of the intensity distribution in that plane is measured and gives $\theta_{max} = \arctan\left(\frac{r_{max}}{f}\right)$ to calculate the $NA = n.\sin(\theta_{max})$.

Another common approach is the far field measurement method [2]. Experimentally, a beam profiler is mounted on a translation stage, and the beam diameter is recorded at a minimum of three different positions along the optical axis in the far field region (i.e. beyond the Rayleigh region). All measurements must be recorded with a consistent metric such as $1/e^2$ (or ISO second-moment diameter). Then, a linear fit of the diameter versus the z distance (for a Gaussian beam the linear slope in far field equals divergence) provides the full angle Θ to get the $NA = n.sin(\frac{\Theta}{2})$.

Both methods are relevant to measure the NA. Nonetheless they both present disadvantages:

+ Focal plane/Fourier plane method needs the use of extra optics. The lens used will introduce aberrations inherent to its quality. Its alignment depends on the wavelength, meaning that in our use case the lens may need to be repositioned for each measurement to compensate for its chromatism. These aberrations are not representative of the laser system and therefore introduce an artifact to the measurement.

+ Far-field method requires a sufficient distance to get several z positions. Therefore, the beam profiler also needs to be realigned at each position.

Although perfectly acceptable in R&D, these methods can be difficult and time consuming in practice, which represent a limitation in production environments due to the volume of parts to test.

"All you need is …"
… a Shack-Hartmann wavefront sensor!

However, there is another approach for determining the NA of a single-mode laser beam. This method uses the measured diameter of the beam and the distance between the measuring device and the source. This distance can be defined as the radius of curvature (ROC) of the beam entering the device, as illustrated in Figure 2.

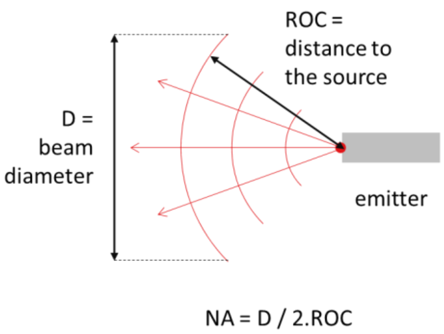

Figure 2. Formula and scheme of the NA value

Conveniently, both parameters can easily be determined in one single-shot measurement with a Shack–Hartmann wavefront sensor (SHWFS). It measures both the phase and the intensity distribution of a laser beam at one position. From the phase -more precisely, the curvature of the wavefront (ROC)- the distance to the source is estimated, and from the intensity profile, the diameter of the beam (D). No movement of the sensor is required, nor realignment. Furthermore, as these two parameters are completely uncorrelated, the NA determination is even more robust. Additionally, no additional relay optics between the laser and the sensor is necessary anymore, as in the beam profiler approach, removing any uncertainty related to it.

Three different beams, three different wavelengths, and one Shack-Hartmann to measure them all.

One of the main advantages of SHWFS technology for this use case is that it is achromatic over a large spectral range. This means it can perform measurements at the blue, green, or red wavelengths right out of the box, with no additional recalibration or realignment.

In conclusion, using the SHWFS allows to:
+ determine the numerical aperture without having to translate the sensor or add beam shaping optics.
+ characterize directly the multiple wavelengths without having to readjust the setup for each of them.

Experimental determination of the NA value in one single absolute measurement.

In this experiment, we will determine the NA value of each wavelength of the Neptune laserchip using only a HASO 126 BROADBAND wavefront sensor (specifications displayed in Figure 3) associated with Imagine Optic's WAVEVIEW metrology software.

Pupil Size	Wavelength	Absolute Accuracy (RMS)	Repeatability
13.8x10.2 mm²	350-1100 nm	350–600 nm ≤ 6 nm 600–1100 nm ~ λ/100	<λ/200 RMS

Figure 3. Overview of HASO 126 BROADBAND specifications

The setup is extremely simple. The HASO 126 BROADBAND is placed directly in front of the laser source, at such a distance that the laser beam is fully included within the analysis pupil without clipping on the edge of the sensor (see Figure 4).

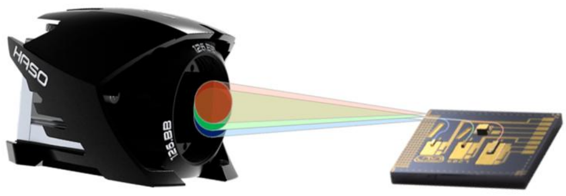

Figure 4. Experimental setup

The maximum pupil size, i.e. the largest diameter that can be measured, is approximately 10 mm. Therefore, the HASO 126 BROADBAND sensor must be placed at a distance of at most 125 mm from the source.

The protocol is also straightforward:

+ Switch on the 1st wavelength and perform, with WAVEVIEW user interface, a simultaneous acquisition with averaging of the wavefront and the intensity, which are saved in a file for later post processing.
+ Then, switch off this wavelength, switch on the 2nd wavelength and
+ Repeat the process until the 3rd wavelength is acquired.

WAVEVIEW is used to reconstruct the wavefront error map and plot it (Figure 5). This wavefront map can be displayed in either 2D or 3D: we observe that the main component is sphere, corresponding to the curvature of a diverging beam, as expected.

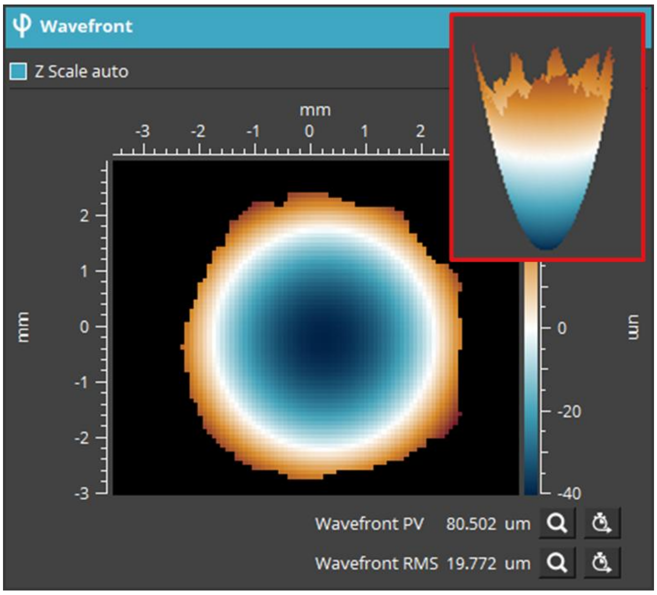

Figure 5. Wavefront error map of the blue wavelength of Neptune laserchip. On the top right corner, the corresponding 3D display of the wavefront

The software interface calculates the Radius of Curvature (ROC) parameter, which can be seen in the beam 'Parameters' windows (see Figure 6).

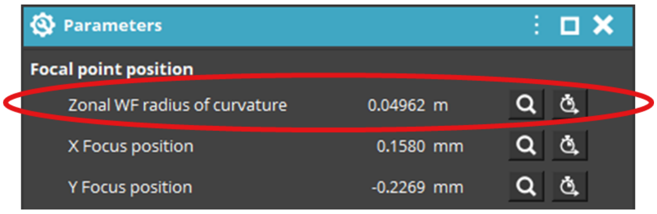

Figure 6. Beam parameters window. Circled in red is the ROC value

WAVEVIEW also computes the intensity map of the beam, which can conveniently be used to measure the beam diameter (D) at a desired intensity threshold, for example at $1/e^2$. For that purpose, 1D intensity profiles can be plotted (their center and orientation can be tuned by the user), as displayed in Figure 7 and values can be exported if necessary for numerical analysis.

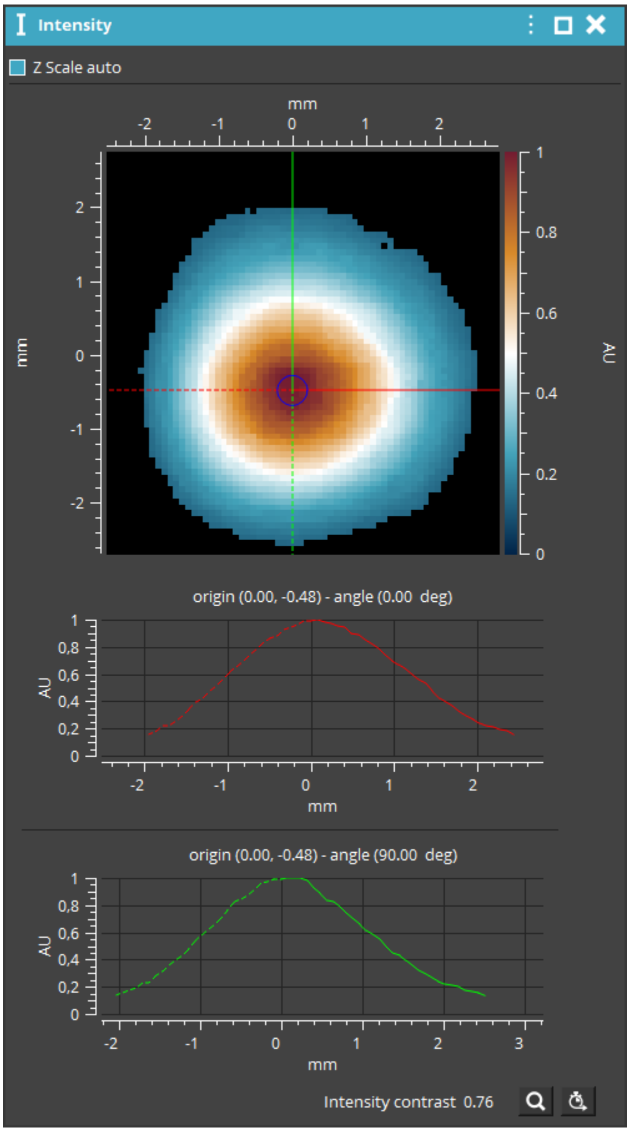

Figure 7. Intensity map of the blue wavelength with a threshold of 1/e² (top). Intensity profiles along the X-axis, plotted in red, and Y-axis plotted in green (bottom)

We can now calculate and compare the NA of each wavelength on the Neptune laserchip.

Table 1: Calculation of the laser NA for each wavelength

Beam λ	ROC (mm)		Beam diameter at 1/e² (mm)		NA at 1/e²	
	X	Y	X	Y	X	Y
Blue	49.6	49.6	4.57	4.57	0.0461	0.0460
Green	49.5	49.5	6.43	5.93	0.0650	0.0599
Red	51.9	51.9	5.16	4.75	0.0497	0.0457

We can see that the NA is almost the same for each axis of a same wavelength. This demonstrates a beam that is almost perfectly circular.
Manufacturer specifications regarding the NA of the laser are between 0.04 and 0.07. We can see that the NAs calculated using the HASO126 BROADBAND are exactly within this range. Therefore, this laser source was tested as compliant.
Note: taking a closer look at the calculated parameters reveals that the ROC at the red wavelength differs slightly because the laser has shifted relative to the sensor. However, this does not affect the determination of the NA, since the entire beam diameter is still included in the analysis pupil.

To delve deeper into the calculations, Imagine Optic has developed an M² meter that requires only a single shot measurement to characterize the M² in accordance with the norm ISO 11146 (see Figure 8 for the display of the M² option). Therefore, in addition to the NA value, we could also measure the M² of each beam using the same setup and measurement!

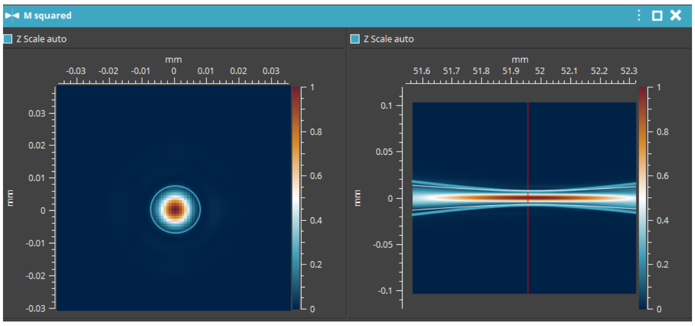

Figure 8. M² feature

Further details on the M² measurement can be found in the application note in our website entitled "M² measurement with CAM SQUARED Application Note"

Conclusion

In this use case, we presented a method for measuring the NA value of a laser beam using only a SHWFS. We also demonstrated how simple such a measurement is, and showed how versatile it is for measuring different wavelengths. In addition, we enlightened the simplicity of the data processing thanks to WAVEVIEW. This metrology protocol demonstrates robustness making it highly suitable for this kind of application. To find out more about Brilliance RGB work, visit their website: BrillianceRGB | The Future is Visible.

References

[1] focal-plane (far-field) beam profiling techniques and experimental procedures, link
[2] M. Gander, R. McBride, J. Jones, T. Birks, J. Knight, P. Russell, P. Blanchard, J. Burnett, and A. Greenaway, "Measurement of the wavelength dependence of beam divergence for photonic crystal fiber," Opt. Lett. 24, 1017-1019 (1999)
[3] All You Need Is Love, song by The Beatles, 1967
[4] The lord of the rings by J.R.R. Tolkien
[5] Datasheet of the HASO BROADBAND link
[6] Brilliance RGB Website: link