New method to diagnose spatial laser beam parameters

G. Nemeş\textsuperscript{1,2}, A. Stratan\textsuperscript{1}, A. Zorilă\textsuperscript{1,3}, Ioana Dumitrache\textsuperscript{1,3}, L. Rusen\textsuperscript{1}, L. Neagu\textsuperscript{1}

\textsuperscript{1}ISOTEST Laboratory, NILPRP, 409 Atomiştilor Str., 077125 Măgurele - Bucharest, Romania
\textsuperscript{2}ASTiGMAT\textsuperscript{TM}, 3409 Pecky Cedar Ct., Sacramento, CA 95827, USA; gnemes98@hotmail.com
\textsuperscript{3}"Politehnica" University of Bucharest, 313 Splaiul Independenţei, 060042 Bucharest, Romania
Acknowledgments

- **Sponsors:**
  - Ministry of National Education, Romania
  - Co-sponsor: European Fund for Regional Development (EFRD/FEDR)
  - Invited guests - supporting LID-LBC mini-symposium
  - "Horia Hulubei" NIPNE/IFIN, Magurele - Bucharest - sponsoring invited guests
  - Audience - interest

**Official project number and title:** Project POS CCE No. 172 / 2010

"Facility for laser beam diagnosis and ISO characterization / certification of behavior of optical components/materials subjected to high power laser beams / ISOTEST"
OUTLINE

1. Introduction

2. VariSpot™

3. Experiments

4. Results and discussion

5. Conclusion
Goal: Measuring laser beam spatial parameters

ISO 11146-1,2,3 → Classical method

Laser + focusing spherical lens + longitudinally translating camera

Can we find other methods?
Basic concepts

Types of beams (geometrical classification, ISO 11146 -1,2,3)
ST, ASA, RSA, GA

Parameters of interest for: ASA beam                   ST beam
Waist size(s):                   \( w_{0x}, w_{0y}; D_{0x}, D_{0y} \)          \( w_0; D_0 \)
Waist location(s):                   \( z_{0x}, z_{0y} \)                           \( z_0 \)
Beam divergence(s):               \( \theta_x, \theta_y \)                        \( \theta \)
Rayleigh length(s):              \( z_{Rx}, z_{Ry} \)                        \( z_R \)
Beam propagation ratio(s):        \( M^2_x, M^2_y \)                        \( M^2 \)

Methods to measure laser beam spatial parameters
- Classical: Spherical lens and longitudinal (z axis) movement
- New: Cylindrical optics and rotational (angular) movement → VariSpot™
2. VariSpot™

VariSpot™ = New family of zoom optical systems – rotating cylindrical lenses

Originally developed for material processing and medical applications

(12) United States Patent
Nemes

(10) Patent No.: US 6,717,745 B2
(45) Date of Patent: Apr. 6, 2004

(54) OPTICAL SYSTEMS AND METHODS
EMPLOYING ROTATING CYLINDRICAL LENSES/MIRRORS


(12) United States Patent
Nemes

(10) Patent No.: US 7,167,321 B1
(45) Date of Patent: Jan. 23, 2007

(54) OPTICAL SYSTEMS AND METHODS
EMPLOYING ADJACENT ROTATING CYLINDRICAL LENSES

(56) References Cited
U.S. PATENT DOCUMENTS
VariSpot™ principle - simplest example

2 - lens system:
+ Cylindrical lens, cylindrical axis fixed, vertical \((f, 0)\)
+ Cylindrical lens, cylindrical axis rotatable about \(z\) \((f, \beta)\)
Examples: VariSpot™ systems for R&D

FS-300-1-UV-VIS-NIR

FS-500-1-266
Examples: VariSpot™ systems

FL-140-3-VIS (demo unit)  FS-110-1-UV-VIS-NIR (R&D unit)

FS-400-1.3-1064 (industrial unit)
VariSpot™ to characterize spatial beam parameters

Theory ("In theory, there should be no difference between theory and practice, but in practice, there is")

Free-space

\[ D(z) = D_0 \left[ 1 + \frac{(z - z_0)^2}{z_R^2} \right]^{1/2} \]

\[ D(\alpha) = D_m \left[ 1 + \frac{[\sin(\alpha) - \sin(\alpha_0)]^2}{r^2} \right]^{1/2} \]

Equivalence: \( D(z) \leftrightarrow D(\alpha); z \leftrightarrow \sin(\alpha); D_0 \leftrightarrow D_m; z_R \leftrightarrow r; z_0 \leftrightarrow \sin(\alpha_0) \)
VariSpot™ to characterize spatial beam parameters

**Theory: input-output relations (thin lens)**

\[ d_{20} - \text{distance after VariSpot, where the spot is round} \]
\[ d_1 - \text{distance from incoming beam waist plane to VariSpot}^{\text{TM}} \text{ first lens} \]
\[ \alpha = 90^\circ - \beta - \text{control parameter} \]
\[ D_0 - \text{incoming beam waist diameter} \]
\[ \theta - \text{incoming beam divergence (full angle)} \]
\[ z_R - \text{incoming beam Rayleigh length} \]
\[ D(\alpha) - \text{diameter of the round spot at target (CCD camera) plane} \]
\[ D_m - \text{minimum round spot diameter at target plane} \]

\[ d_{20} = f(z_R^2 + d_1^2)/(z_R^2 + d_1^2 - d_1 f) \]
\[ D(\alpha) = D_m \{(1 + [\sin(\alpha) - \sin(\alpha_0)]^2/r^2)^{1/2} \}
\[ D_m = D_0 d_{20}/[d_1(1 + z_R^2/d_1^2)^{1/2}] \]
\[ r = (fz_R)/(z_R^2 + d_1^2) \]

\[ d_1 = f(1 - f/d_{20})/[(1 - f/d_{20})^2 + r^2] \]
\[ z_R = fr/[(1 - f/d_{20})^2 + r^2] \]
\[ D_0 = D_m f/[d_{20}[(1 - f/d_{20})^2 + r^2]^{1/2}] \]
\[ M^2 = (\pi/4)fD_m^2/(\lambda rd_{20}^2) \]
\[ \theta = D_m [(1 - f/d_{20})^2 + r^2]^{1/2}/(rd_{20}) \]
Method of measuring beam parameters using VariSpot™

• Find and measure $d_{20}$ by locating the round spot after VariSpot™

• Measure $D(\alpha)$ at the appropriate target plane (at $d_{20}$) for different $\alpha$
  Include $D_m$, the "angular near-field", and the "angular far-field" for $\alpha$
  Similarity to ISO 11146 standard for near-field and far-field

• Fit $D(\alpha)$ and determine $\alpha_0$, $D_m$, $r$

\[ D(\alpha) = D_m \{1 + [\sin(\alpha) - \sin(\alpha_0)]^2/r^2\}^{1/2} \]

• Recover by calculations the original beam parameters
Precautions at using VariSpot™

Distance $d_{20}$ for the round spot after VariSpot™ is slightly different than the distance to the waist plane $d_{2w}$ for a lens with same $f$, $d_{20} \neq d_{2w}$

![Spot profile in the waist plane, at $d_{2w}$, after VariSpot™](image1)

$\alpha = 0^0$

$D_{20} = 0.156 \text{ mm}$

![Spot profile in the plane of round spot, at $d_{20}$, after VariSpot™](image2)

$\alpha = 10^0$

$\alpha = 0^0$

$\alpha = 20^0$

$D_m = 0.172 \text{ mm} > D_{20}$
3. Experiments

Three configurations

Configuration 1: Classical method, spherical lens + moving camera

Configuration 2: Classical method, VariSpot™ as spherical lens (\(\alpha = 0^0\))

Configuration 3: New method, Varispot™ as rotating optics, get \(D(\alpha)\) at \(d_{20}\)
4. Results and discussions

![Diagram of optical setup](image)

**Configuration 1**

Propagation after lens ("image beam")

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Rel. error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M^2$</td>
<td>1.15</td>
<td>2</td>
</tr>
<tr>
<td>$D_{01}$ (mm)</td>
<td>0.82</td>
<td>5</td>
</tr>
<tr>
<td>$z_{R1}$ (mm)</td>
<td>726</td>
<td>10</td>
</tr>
<tr>
<td>$\theta_1$ (mrad)</td>
<td>1.13</td>
<td>5</td>
</tr>
<tr>
<td>$z_{01}$ (mm)</td>
<td>1895</td>
<td>9</td>
</tr>
</tbody>
</table>

Recovered original beam parameters ("object beam")
Results and discussions

Configuration 2

Propagation after VariSpot™ as spherical lens lens ("image beam")

Recovered original beam parameters ("object beam")

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Rel. error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( M^2 )</td>
<td>1.18</td>
<td>4</td>
</tr>
<tr>
<td>( D_{01} ) (mm)</td>
<td>0.89</td>
<td>6</td>
</tr>
<tr>
<td>( z_{R1} ) (mm)</td>
<td>834</td>
<td>11</td>
</tr>
<tr>
<td>( \theta_1 ) (mrad)</td>
<td>1.07</td>
<td>6</td>
</tr>
<tr>
<td>( z_{01} ) (mm)</td>
<td>1887</td>
<td>11</td>
</tr>
</tbody>
</table>
Results and discussions

Configuration 3

D(\(\alpha\)) after VariSpot\textsuperscript{TM}, in target plane, at \(d_{20}\)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Rel. error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(M^2)</td>
<td>1.18</td>
<td>6</td>
</tr>
<tr>
<td>(D_{01}) (mm)</td>
<td>0.86</td>
<td>6</td>
</tr>
<tr>
<td>(z_{R1}) (mm)</td>
<td>773</td>
<td>12</td>
</tr>
<tr>
<td>(\theta_i) (mrad)</td>
<td>1.11</td>
<td>7</td>
</tr>
<tr>
<td>(z_{01}) (mm)</td>
<td>1916</td>
<td>13</td>
</tr>
</tbody>
</table>
Experiments - Configuration 3. Corrections

Corrections for thick optical system: $f_{Cyl} = 302$ mm

VariSpot™ as a spherical lens for $\alpha = 0^\circ$, finding its corrected effective focal length, $f_C$

- Measuring: He-Ne laser + 4x BE + VariSpot™ $\rightarrow$ finding waist position $\rightarrow d_{2w} = f_C = 300$ mm

- Data calculated for $f_C = 300$ mm and for $f_C = 299$ mm $\rightarrow$ Better results for $f_C = 299$ mm

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Lens, $f = 338$ mm</th>
<th>VariSpot™, $f_C = 300$ mm $\alpha = 0^\circ$</th>
<th>VariSpot™, $f_C = 300$ mm Variable $\alpha$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M^2$</td>
<td>$1.15 \pm 2%$</td>
<td>$1.18 \pm 4%$</td>
<td>$1.18 \pm 6%$</td>
</tr>
<tr>
<td>$D_{01}$ (mm)</td>
<td>$0.82 \pm 5%$</td>
<td>$0.89 \pm 6%$</td>
<td>$0.86 \pm 6%$</td>
</tr>
<tr>
<td>$z_{R1}$ (mm)</td>
<td>$726 \pm 10%$</td>
<td>$834 \pm 11%$</td>
<td>$773 \pm 12%$</td>
</tr>
<tr>
<td>$\theta_1$ (mrad)</td>
<td>$1.13 \pm 5%$</td>
<td>$1.07 \pm 6%$</td>
<td>$1.11 \pm 7%$</td>
</tr>
<tr>
<td>$z_{01}$ (mm)</td>
<td>$1895 \pm 9%$</td>
<td>$1887 \pm 11%$</td>
<td>$1916 \pm 13%$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Lens, $f = 338$ mm</th>
<th>VariSpot™, $f_C = 299$ mm $\alpha = 0^\circ$</th>
<th>VariSpot™, $f_C = 299$ mm Variable $\alpha$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M^2$</td>
<td>$1.15$</td>
<td>$1.18$</td>
<td>$1.18 \pm 6%$</td>
</tr>
<tr>
<td>$D_{01}$ (mm)</td>
<td>$0.82$</td>
<td>$0.87$</td>
<td>$0.84 \pm 6%$</td>
</tr>
<tr>
<td>$z_{R1}$ (mm)</td>
<td>$726$</td>
<td>$791$</td>
<td>$743 \pm 11%$</td>
</tr>
<tr>
<td>$\theta_1$ (mrad)</td>
<td>$1.13$</td>
<td>$1.10$</td>
<td>$1.13 \pm 7%$</td>
</tr>
<tr>
<td>$z_{01}$ (mm)</td>
<td>$1895$</td>
<td>$1850$</td>
<td>$1880 \pm 13%$</td>
</tr>
</tbody>
</table>
6. Conclusion

- Demonstrated new method to measure spatial beam parameters
- Uses rotating cylindrical optics, fixed CCD camera position (one translation only)
- "Propagation" formulae analogue to classical method (free-space propagation)
- ISO 11146 -1 recommendations (near-field, far-field measurements) have a straightforward analogue and can easily be implemented
- Reasonable small relative errors ($\leq 15\%$) for preliminary measurements
- Needs more work on corrections
- Needs more experiments
- Needs detailed error propagation analysis
- Needs extension/experiments to measure ASA beams (theory does exist)