Enhancement of Deep Ultraviolet Output In Fiber-Coupled Laser-Driven Light Sources

Paul A. Blackborow, Donald K. Smith, Deborah S. Gustafson, Matthew M. Besen, Huiling Zhu, Tseten Lungjangwa

Energetiq Technology, Inc., Woburn, MA, USA
Agenda

- Background: Laser-Driven Light Source (LDLS™)
- Fiber-Coupled LDLS: Advantages and Challenges
- Fiber Degradation in Deep Ultraviolet
- Fiber-Protection Technology: Results
- Applications.
Today’s Lamp Technologies

- Mercury Discharge
- Xe & Hg Arc
- Excimer
- Deuterium
- Metal Halide
- Halogen

All have limitations in:
- Brightness
- Lifetime/Stability
- Spectral Range
Limitations of Arc-Lamps

- Arc-Lamps use electrodes to conduct electrical current through the gas heat the gas to high temperature
  - The electrodes limit the temperature of the gas
    - Limited temperature leads to limited DUV
  - The electrodes erode and shorten lamp lifetime
  - Arc flicker reduces effective brightness and adds noise

| Broadband | ✓ |
| Brightness | ✓ |
| Stability | ✗ |
| Lifetime | ✗ |

DUV output falls below 300nm

(Source: Hamamatsu)
Limitations of Deuterium Lamps

- Limited wavelength range ~190nm – 400nm
- Low brightness, relatively large plasma
- Short life: 500-1000hrs to 50% output

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<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td>Broadband</td>
<td>X</td>
</tr>
<tr>
<td>Brightness</td>
<td>X</td>
</tr>
<tr>
<td>Stability</td>
<td>√</td>
</tr>
<tr>
<td>Lifetime</td>
<td>X</td>
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Source: Hamamatsu
Limitations of Tungsten Lamps

- Short lifetime, large filament area, low power <400 nm
- Usually combined with Deuterium lamp to cover broad spectrum
  - Gap in spectrum around 400nm
  - Low brightness from 2 separate emitters
  - Changing spectrum from 2 different lifetimes

<table>
<thead>
<tr>
<th>Feature</th>
<th>Status</th>
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<tbody>
<tr>
<td>Broadband</td>
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<tr>
<td>Brightness</td>
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<tr>
<td>Stability</td>
<td>✓</td>
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<tr>
<td>Lifetime</td>
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Laser-Driven Light Source: Principle of Operation

Beam from CW Laser

Laser Beam Focusing Optics

Lamp Enclosure Containing Gas(es)

High Intensity Plasma

Broad Spectral Output

• US Patent # 7,435,982
# EQ-99 Plasma Images

<table>
<thead>
<tr>
<th></th>
<th>Lamp House 34</th>
<th>Lamp house 39</th>
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<tbody>
<tr>
<td>FWHM horizontal, μm</td>
<td>64</td>
<td>61</td>
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<tr>
<td>FWHM vertical, μm</td>
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<td>140</td>
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<td><img src="image2.png" alt="Image" /></td>
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EQ-99X Spectral Distribution

- EQ-99X
- 30Watt Deuterium Lamp

Typical Data
**LDLS™: Stable & Long-Life**

### Change in Broadband Output /1000 Hrs (Typical)

- **EQ-1500**: ~ -1%  
  Lamp Life Hrs: >9,000

- **EQ-99X**: ~ -1%  
  Lamp Life Hrs: >9,000

- **30W D2 Lamp**: -50% (depending on model)  
  Lamp Life Hrs: ~1000 (50% Output)  
  Source: Heraeus Data Sheet

- **75W Xe Lamp**: -25% to -50% (depending on model)  
  Lamp Life Hrs: ~2000 (50% Output)  
  Source: Hamamatsu Data Sheet
Fiber Coupled LDLS

Advantages and Challenges
LDLS™ with Fiber-Coupled Output

How it Works:

- Laser power sustains plasma
- Wide angle collection refocused to fiber coupler
  - Integrated high-performance ellipsoidal collection optic
  - Couples across full wavelength range
  - DUV - 2100nm
EQ-99FC Typical Performance:
with 230µm diameter, 0.22NA, 1m long, DUV/Vis solarization resistant fiber

<table>
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<tr>
<th>Wavelength, nm</th>
<th>Spectral Power, µW/nm</th>
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<tr>
<td>170</td>
<td>1</td>
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<tr>
<td>270</td>
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<td>870</td>
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Power ratios

<table>
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<tr>
<th>Fiber (µm)</th>
<th>Multiplier</th>
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<tr>
<td>230</td>
<td>1</td>
</tr>
<tr>
<td>450</td>
<td>2.02</td>
</tr>
<tr>
<td>600</td>
<td>2.26</td>
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**Typical Data**
Advantages and Challenges

- Small plasma spot ~100µm allows coupling into small diameter fibers
  - 115µm, 230µm typically used
- Delivers high brightness into fiber

- But...

- High intensity light delivered by LDLS can damage fibers
  - Light is attenuated over time, mostly in DUV
  - Fibers may need replacing more frequently than desired.
**Degradation in DUV after 160hrs.**

- Even ‘solarization resistant’ UV-Vis fibers attenuate in the 200-300nm range when used with ultrabright light sources such as LDLS.
  - Typical DUV life is a few hundred hours.

Typical Data
Fiber-Protection Technology™

- Energetiq’s proprietary Fiber-Protection Technology™ enables order of magnitude longer life in Deep Ultraviolet
- Protection is effective over long periods >2000hrs
EQ-99XFC Spectral Distribution

EQ-99XFC Typical Performance:
with 230µm diameter, 0.22NA, 1m long fiber

Typical Data

<table>
<thead>
<tr>
<th>Fiber Size (µm)</th>
<th>Estimated Multiplier</th>
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<tr>
<td>115</td>
<td>0.3</td>
</tr>
<tr>
<td>230</td>
<td>1</td>
</tr>
<tr>
<td>450</td>
<td>2</td>
</tr>
</tbody>
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Applications

- UV-Vis Spectrometry
- Monochromator Source
- PEEM
- Atomic Absorption Spectroscopy
- Materials Characterization
- Environmental Analysis
- Hyperspectral Imaging
- Gas Phase Measurements
- Advanced Microscopes
- Endoscopes/Borescopes
DUV Microscope with Integrated EQ-99FC
DUV Microscope Configuration at Boston University

- Camera
- Emission Filter
- Ultrafluar Objective
- UV-Kond Condenser
- Bandpass Filters
- 1mm Fiber from EQ-99
Compare to 600µW UV LED, 280 nm

( and you only get 60 microwatts from UV LED at 260 nm…)

- LED, unfiltered, 5 sec exp.
- LED, filtered, 5 sec exp.
- EQ-99, filtered, 10 msec exp.

Both systems fiber coupled through identical optics.

Exposure rate 250 times faster.
Mapping of Intracellular Protein & Nucleic Acid

By using imaging spectrophotometry with paired images in the 200- to 280-nm wavelength range, we have directly mapped intracellular nucleic acid and protein distributions across a population of Chinese hamster ovary (CHO-K1) cells. A broadband 100× objective with a numerical aperture of 1.2 NA (glycerin immersion) and a novel laser-induced-plasma point source generated high-contrast images with short (∼100 ms) exposures and a lateral resolution nearing 200 nm that easily resolves internal organelles.

The approach allows absolute mass measurements with no special sample preparation or staining. It can be used in conjunction with normal fluorescence microscopy and with relatively modest modification of the microscope.

Dan Ehrlich et.al., Boston University
Micro-Endoscopy
Micro-Endoscopy

- Traditional endoscopes are designed around lower brightness light sources such as Tungsten-Halogen and Xenon-Arc.
  - The relatively large emission spots of those sources match well to large endoscope fibers ~3-6mm
  - Applications are often light-starved if the illumination fiber needs to be <1mmØ

- New Micro-Endoscope applications need to couple light efficiently into much smaller fibers (<1mmØ)
  - Fiber-coupled LDLS is a good match for these applications.
  - Excellent spectral coverage for good color rendition
  - Much longer life for lower costs
Spectrally Encoded Endoscopy

- Excellent work at Bar-Ilan University to design and build a novel micro-endoscopy device
Spectroscopic Ellipsometry
Spectroscopic Ellipsometry

- Widely used in a variety of markets
  - Semiconductor
  - Thin-Film
  - Materials science

- Broadband illumination DUV-Vis-NIR from a single light source is very beneficial
  - Simpler optics
  - Fiber-coupling can ease integration

- More light in DUV allows more precise measurements of certain thin-films
Imaging Spectroscopic Ellipsometer

- 200-2000nm measurement range
- Fiber-Coupled LDLS
- Long operating life with high uptime
- Lateral resolution to below 1µm
Detection of Explosives by Differential Hyperspectral Imaging
Detection of Explosives by Differential Hyperspectral Imaging

Fig. 2 (a) Differential reflectograms of some common explosive materials (TNT, C4, ANFO, and PETN). (b) Differential reflectograms of various nonexplosive materials (white powders: flour, Splenda, salt, and typical background materials, such as a red jacket and denim jeans).

University of Florida, Gainesville
Detection of Explosives by Differential Hyperspectral Imaging

Fig. 1 Schematic representation of the differential reflectometry scanner (a). Picture of an actual device scanning a bag (b). (Adapted with changes from Ref. 4.)

University of Florida, Gainesville
Summary

- Laser Driven Light Sources produce very high brightness across DUV-Vis-NIR spectrum, 170nm – 2100nm
  - Small, stable spot means easy coupling to small fibers

- High intensity from LDLS can degrade fibers in the DUV

- Fiber Protection Technology increases DUV by an order of magnitude and extends life to >2000hrs

- A wide range of applications can use the unique combination of High Brightness, Broad-Spectrum and Long-Life found in the LDLS
The brightest, most consistent broadband light sources since the sun

EQ-99X  EQ-99XFC  EQ-1500
Thank You

______________________________
Paul Blackborow
www.energetiq.com
info@energetiq.com