Compact Radiation Sources Using Dielectric Laser Accelerators

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Zhirong Huang (SLAC, Stanford)  
Yenchieh Huang (NTSU)

4th European Advanced Accelerator Concepts Workshop, Elba, Italy  
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Dielectric Laser Accelerator (DLA) Concept: Towards an “Accelerator on a Chip”

Required lasers are MHz rep rate, low pulse energy, wallplug efficiency ~ 30%

Dielectric materials can withstand GV/m fields and kilowatts of average power

Can be mass produced using techniques of the integrated circuit industry.

DLA research aims to produce ultracompact nanofabricated devices for particle acceleration, powered by efficient solid-state lasers.
High Brightness Photocathodes

<table>
<thead>
<tr>
<th></th>
<th>W tip (Erlangen)</th>
<th>W tip w/diamond (Erlangen)</th>
<th>LaB$_6$ nanowire (Erlangen)</th>
<th>diamond pyramid (Los Alamos)</th>
<th>Si nanotip</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R$ (nm)</td>
<td>(&lt;1.0)</td>
<td>170</td>
<td>(1.5)</td>
<td>&lt;10</td>
<td>15</td>
</tr>
<tr>
<td>max $e^-$/pulse</td>
<td>625</td>
<td>1000</td>
<td>20</td>
<td>12000</td>
<td>1000</td>
</tr>
<tr>
<td>$\varepsilon_n$ (nm)</td>
<td>0.1</td>
<td>0.35</td>
<td>0.1</td>
<td>?</td>
<td>0.25</td>
</tr>
<tr>
<td>$B_{5D,n}$ (A/cm$^2$)</td>
<td>6.7e12</td>
<td>1e10</td>
<td>1.1e12</td>
<td>?</td>
<td>1e12</td>
</tr>
<tr>
<td>stability</td>
<td>30 min</td>
<td>&gt;1 hour</td>
<td>?</td>
<td>&gt;1 hour</td>
<td>&gt;1 hour</td>
</tr>
<tr>
<td>integrated</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
</tr>
</tbody>
</table>
Integrating the components for a 1 MeV accelerator

see talk by P. Hommelhoff (Wed Plenary)

Stanford “glassbox” test system

compact electron gun w/electrostatic lens

optimized DLA components via inverse design


N. Sapra, et al., in review Science (2019)

courtesy T. Hirano (Hamamatsu, visiting scientist at Stanford University)
potential areas of industry interest
• Biomedicine industry
  -- Radiation therapy
• Semiconductor industry
  -- low-power EUV for mask/wafer inspection/calibration

potential areas of scientific interest
• Nano- or micro-beam for radiobiology and radiation chemistry
• Ultrafast electron diffraction, X-ray pulses at sub-fs time scales
Strawman Parameters for a DLA Based Medical Linac

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Desired Capability</th>
<th>Unique DLA Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron energy</td>
<td>1-20 MeV</td>
<td>Single-wafer design with 1 GV/m gradient</td>
</tr>
<tr>
<td>Useful dose</td>
<td>1 Gray/sec</td>
<td>2000 e- per bunch; 2 MHz rep rate</td>
</tr>
<tr>
<td>Treatment Volume</td>
<td>5-10 cm³</td>
<td>Directed (vs omnidirectional) beam and on-chip deflection to scan tumor area</td>
</tr>
<tr>
<td>Small footprint</td>
<td>~ 1 cm x 10 cm</td>
<td>2um wavelength optical scale device with 2 cm active linac length</td>
</tr>
<tr>
<td>Wall Plug Power</td>
<td>&lt; 100 Watt</td>
<td>Modest 2.9% wall-plug to electron efficiency</td>
</tr>
</tbody>
</table>

- Electron penetration depth set by adjusting beam energy.
- Customized dose distribution by “rastering” with steering elements.

Simulations by B. Fahimian, B. Loo (Stanford)  

A small-footprint medical accelerator directly maps to DLA’s unique features.
### Radiation Parameters of Interest for Industrial Applications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Desired specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>UV to X-ray, broad or narrow band</td>
</tr>
<tr>
<td>Brilliance</td>
<td>$&gt; 10^{10}$ photon/(sec mm$^2$ mrad$^2$ 0.1%BW)</td>
</tr>
<tr>
<td>Brightness</td>
<td>$&gt; 10^8$-$10^{12}$ photons/(sec sr)</td>
</tr>
<tr>
<td>Pulse width</td>
<td>&lt; Sub femto second for High speed image</td>
</tr>
<tr>
<td></td>
<td>&lt; 1ns for inspection</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>$&gt; 1$-100 MHz</td>
</tr>
<tr>
<td>Unit cost</td>
<td>Depends on application</td>
</tr>
</tbody>
</table>

- Inspection for semiconductor wafer, mask
- Spectroscopy
- Imaging

slide courtesy T. Hirano, Hamamatsu
Components of a DLA Light Source

Overall goal: The demonstration of an integrated multi-stage particle “accelerator on a chip” will validate the potential to scale to energy levels of interest for “real-world” applications.

1. On-chip electron source
2. DLA structure development: (a) subrelativistic, (b) relativistic
3. Multi-staged acceleration
4. Coupling of laser to DLA
5. Laser-driven undulator
An equal superposition of the TE and TM fundamental modes produces a pure deflection mode (i.e. no $E_z$ component)!

A. Ody, R. J. England, Z. Huang, AAC 2018 and SLAC-PUB
DLA's attosecond bunch structure raises the possibility of making attosecond radiation pulses

Optical structures naturally have sub-fs time scales and favor high repetition rate operation

Pre-proposal for NSF Science and Technology Center (June, 2019)

Recent experiments have demonstrated (a) laser-driven particle deflection in nanophotonic devices to generate and measure trains of sub-fs electron bunches and (b) laser-driven net acceleration and energy gain of these bunches as a function of relative laser phase.

See also talks by P. Hommelhoff (Wed Plenary), N. Shönenberger (Mon WG3)
EUV Attosecond Frequency Comb

Modelocking scheme proposed could enable attosecond radiation pulses (R. J. England, Z. Huang, FLS 2018)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Energy</td>
<td>MeV</td>
<td>40</td>
</tr>
<tr>
<td>Microbunch Charge</td>
<td>fC</td>
<td>10</td>
</tr>
<tr>
<td>Undulator Period</td>
<td>µm</td>
<td>250</td>
</tr>
<tr>
<td>Number of periods / Delay Modules</td>
<td>#</td>
<td>10 / 100</td>
</tr>
<tr>
<td>EUV Photon Energy</td>
<td>eV</td>
<td>50</td>
</tr>
<tr>
<td>Radiated Pulse Energy</td>
<td>nJ</td>
<td>100</td>
</tr>
</tbody>
</table>
Possibility of On-Chip Coherent Radiation Sources (EUV to Mid-IR)

An integrated nanoemitter combined with Smith-Purcell radiator is of interest as a tunable on-chip source of EUV to mid-IR for telecom, LIDAR, and photon science.

ACHIP goals

Develop an efficient tuneable radiator using inverse design with Silicon (or other materials) Target 50-200 nm EUV and IR to mid-IR.

Initial experiments could be conducted using a commercial DC electron gun.

Fabrication prototype for silicon-based on-chip field emission source (Solgaard Group, Stanford)
DC Electron Test Stand for DLA Radiation Studies

Experimental Plan:

1. Beam characterization study (complete – emittance ~ 20 nm-rad)
2. Incoherent IR radiation from Silicon grating (in progress now)
3. Coherent SP and Cherenkov studies using optimized structures (next 6-9 months) for EUV to mid-IR
Wavelength Tunability – FDTD Simulation

Note: example parameters chosen to benchmark numerical method and do not necessarily correspond to a planned experiment.

**Parameters:**
Grating period : 50 nm  
Number of gratings : 20-55 units.  
Electron energy : 4-8 keV  
Material : Si, Au coating  
observation at 90° to e-beam axis

\[ \lambda_{sp} = \frac{\lambda_p}{n} \left( \frac{1}{\beta} - \cos \theta \right) \]

simulation by N. Cohen (Technion) under ACHIP Radiation group;  
see Massuda, et al, ACS Photonics 2018, 5, 3513–3518 for description of methodology
Power Estimation for 200 µm Grating with 666 periods and 1 µA beam current

\[ P_\omega = \frac{1}{2} \int E \times H^* \cdot \hat{y} \, dA \]

\[ \Delta \omega = 2 \pi \Delta f \quad ; \quad \Delta f = 5 \text{ THz} \]

\[ U_e = \frac{P_\omega}{\Delta \omega} = \text{Energy / e / period} \]

\[ P_{\text{rad}} = U_e \frac{I_{\text{beam}}}{q} N_{\text{periods}} \]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grating period</td>
<td>( \lambda_p )</td>
<td>300 nm</td>
</tr>
<tr>
<td>Energy</td>
<td>( T_0 )</td>
<td>30 keV</td>
</tr>
<tr>
<td>Velocity</td>
<td>( \beta )</td>
<td>0.328</td>
</tr>
<tr>
<td>Angle</td>
<td>( \theta )</td>
<td>90 deg</td>
</tr>
<tr>
<td>Central radiation wavelength</td>
<td>( \lambda_{\text{rad}} )</td>
<td>913 nm</td>
</tr>
<tr>
<td>Power in +y direction</td>
<td>( P_\omega )</td>
<td>1.04e-10 W</td>
</tr>
<tr>
<td>Energy/e/period</td>
<td>( U_e )</td>
<td>3.3e-24 J</td>
</tr>
<tr>
<td>No. of periods</td>
<td>( N_{\text{periods}} )</td>
<td>666</td>
</tr>
<tr>
<td>Beam current</td>
<td>( I_{\text{beam}} )</td>
<td>1 µA</td>
</tr>
<tr>
<td>Photon flux</td>
<td>( I_{\text{beam}} )</td>
<td>3.5e11 s⁻¹</td>
</tr>
<tr>
<td>Total power</td>
<td>( P_{\text{rad}} )</td>
<td>13.7 nW</td>
</tr>
</tbody>
</table>
Interestingly, the simulation predicts more power flow into the silicon than into the vacuum region above the grating. However, the absorptive loss of silicon (not included here) may reduce this discrepancy.
Maximum Power Emission

Silicon $n = 3.43$, Electron Energy = 50 keV, Structure period = 1 µm; Structure length = 200 µm; linear material and neglect wavelength dependence of index $n$

Suggests that for typical DLA impact parameters ($r \sim 0.1$ to 0.2 µm) radiation power can theoretically be in the nW range for nA beam current.

May require specialized structures (e.g. inverse design).

Potential for coherent enhancement via microbunched beams.

Possible coherent radiations from a periodic Si structure

Simulations by Y-Ch. Huang, Tzuchih Liu (National Tsing Hua Univ)
CST Simulation for Si grating (@ 20 ps): Coherent TM Radiation at 1.1 \(\mu\)m detected at 90\(^{th}\) period

30 keV, round hard-edge beam with \(I = 10\) nA/\(\mu\)m\(^2\)

Zero-loss Silicon with 100 periods (50 \(\mu\)m)

Z-Polarization – TM (referenced to the top grating surface)

\(\Delta \omega/\omega \approx 0.4\%\)

@ 7 ps

\(\sim 1\) mW/m\(^2\)

in groove

in Silicon
Conclusions

- A sub-group of ACHIP has been established to explore radiation generation and applications for DLA technology
- Workshop conducted in March outlined future directions for attosecond science, microscopy, radiobiology, and medical applications
- A laser driven undulator combined with a DLA provides a potential future compact source of coherent attosecond undulator radiation for EUV or X-ray production
- Near-term experiments planned to study coherent radiation generation in silicon and other DLA-like structures (inverse radiative processes of the acceleration mechanism)
- DC Electron gun test stand now in operation to facilitate these investigations. Partnerships with Technion, NTHU for experiment and simulation.
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*blue* = students;  * = current Bob Siemann fellows
Thank you!

Group photo, ACHIP collaboration meeting at DESY, Hamburg, Germany, Sept 19-21, 2018.

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http://achip.stanford.edu
http://slac.stanford.edu/dla

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