High Power Pulsed-fiber Laser Based Driver for Efficient 13.5-nm EUV Generation Using Tin-doped Droplet Targets

Kai-Chung Hou[1], Simi A. George[2], Aghapi G. Mordovanakis[1], Kazutoshi Takenoshita[2], John Nees[1], Martin Richardson[2], and Almantas Galvanauskas[1]
[1]. Center for Ultrafast Optical Sciences, University of Michigan
[2]. Laser Plasma Laboratory, Townes Laser Institute, College of Optics and Photonics, University of Central Florida

High Power Fiber Laser EUV Driver Architecture for 400W FLPP in-band EUV Source

Fiber Laser Technology Advantages

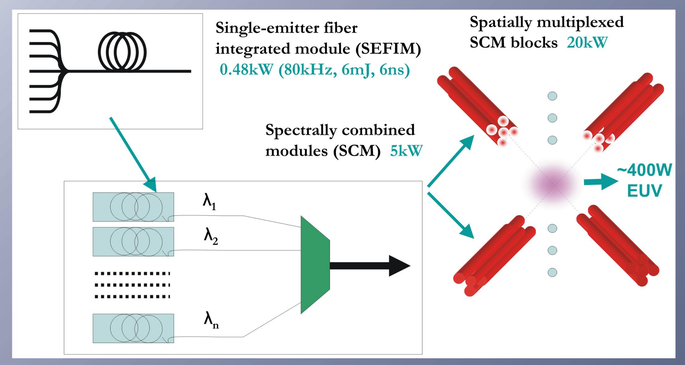
- Low cost:
  - capital investment
  - cost of ownership
- High plug efficiency
- Long lifetime/reliable
- Small footprint (<10 ft².)
- Technical:
  - High repetition rate
  - High beam quality

New and emerging technology:

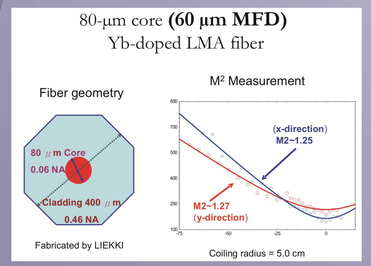
- Continuously increasing market share
- Continuing advances in technology
  - Novel fibers and components
  - Advances in diode pumping
- Further R&D efforts needed for fiber laser EUV driver

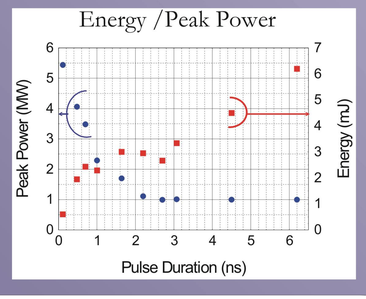
Example System Characteristics

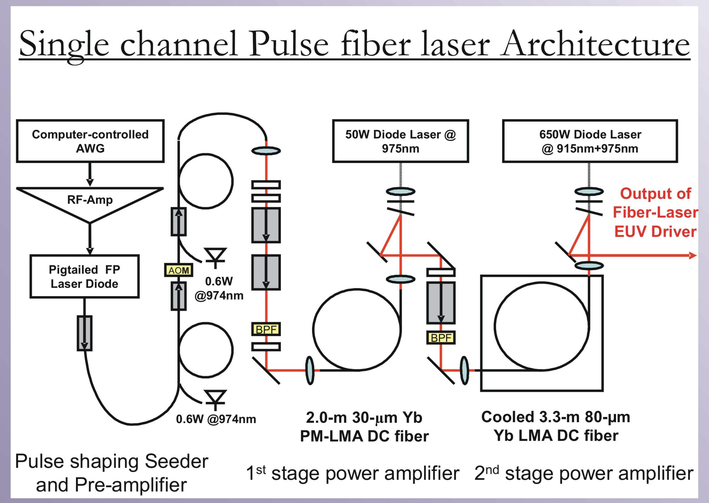
	SEFIM (70 kHz – target limited)	SCM (12 SEFIM combined)	Spatially Multiplexed System (4 SCM multiplexed)
Pulse energy	6 mJ (fiber limited)	72 mJ	240 mJ
Pulse duration	6ns		
Repetition rate	1kHz - 70kHz		
Power	420 W	5kW	20kW
Beam quality	$M^2 = 1.1 – 2$	$M^2 = 1.1 – 2$	———



400W Single Channel Fiber Laser Development







Arbitrary Temporal Pulse Shaping

- Arbitrary pulse shaped seed enables
  - EUV optimization by changing pulse duration, pulse shape and pre-pulses
  - Compensation of pulse temporal shape deformation due to gain saturation
- High speed PC-interfaced programmable arbitrary waveform generator
  - High temporal resolution of 1-ns with 200ps rise time
  - Large dynamic range of pulse duration from 1ns to 4ms
  - High vertical resolution of 12 bit

Comparison between Numerical and Experimental Temporal Pulse Re-shaping

•Pulse reshaping due to saturation when output energy is close to saturation fluence:

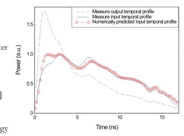
•80μm fiber, LP_{01} mode field diameter = 60 μm ~ E_{sat} = 1.8mJ

•Saturated Intensity Gain as function of time within the pulse

$$G(t) = 1 + (G_0 - 1)\exp[-U_{out}(t)/U_{sat}]$$

•Required input pulse shape for a specific output pulse shape and energy can be numerically calculated

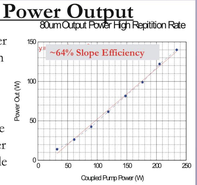
$$I_{in}(t) = \frac{I_{out}(t)}{1 + (G_0 - 1)\exp[-\frac{\int_{-\infty}^{t} I_{out}(t)dt}{U_{sat}}]}$$



Example of numerically obtaining the input seed pulse including the effect of saturated gain from an output pulse of known shape and energy. The example shown here is for 5-mJ 1064-nm amplified output pulse from a 80- μ m Yb-doped fiber

Average Power Output

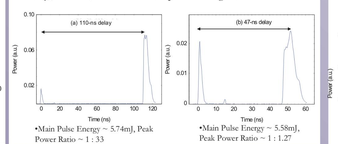
- Current average power limited by degradation of fiber jacket.
- Fiber with improved jacket available and should be able to have >300W average power with 650W of available pump power



140W of average power achieved, coating degradation is now the limiting factor

Pre-pulses Capability from AWG for Plasma Temperature Optimization

- AWG is also capable of generating prepulses of programmable delay, contrast, duration and shape from single channel laser

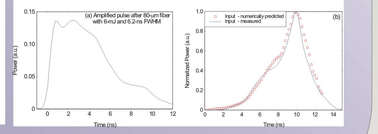


•Main Pulse Energy ~ 5.74mJ, Peak Power Ratio ~ 1 : 33

•Main Pulse Energy ~ 5.58mJ, Peak Power Ratio ~ 1 : 1.27

Pulse Shaping

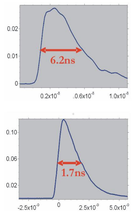
- High energy extraction will require pre-shaped seed pulse with slow rising edge to avoid sharp rising edge due to gain saturation
- 6.2mJ corresponding to more than 3 times saturation and ~72% of extractable energy from 80μm fiber by reshaping
- Numerical analysis shows good agreement for the measured and calculated pulse temporal shape



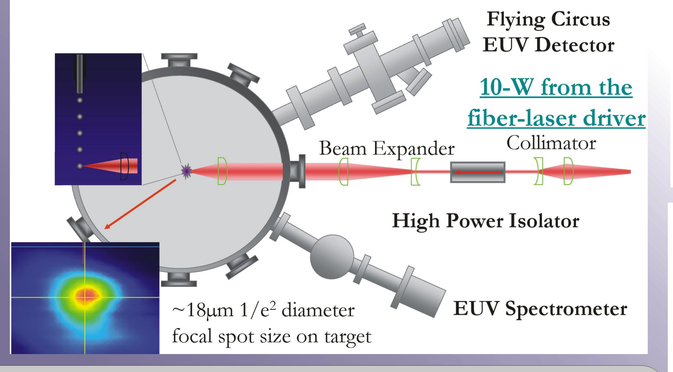
Demonstration of Efficient EUV Generation with Single Channel Emitter

Laser Parameters Used

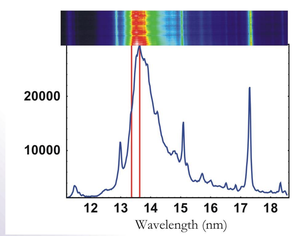
- Repetition Rate ~1.75kHz for optimization study
- Two sets of laser parameters were used
  - Longer pulses – 5.7mJ, 6.2ns ~0.92MW peak power(~72% of extractable energy from 80μm fiber)
  - Shorter pulses – 2.9 mJ, 1.7ns ~1.7MW peak power
- Prepulse Parameters Used
  - Delay 19ns~100ns
  - Peak power contrast 1:1 to 1:30
  - Prepulse duration ~2~5ns, main pulse duration ~4.5~6ns
- Measured spot size <18μm $1/e^2$ (f/3) with intensity up to 6.7×10^{11} W/cm²



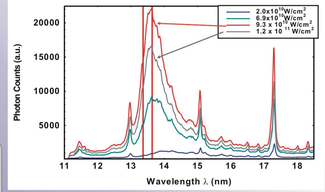
UCF Experiment Setup



Spectrum with Tin-doped Droplet Target



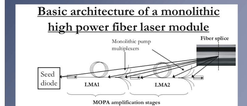
Spectra with Different Intensity Levels



CE~2.1% demonstrated by Fiber-laser EUV Driver

Monolithic Power Scalable Fiber Laser Technology - Current Development and Future Outlook

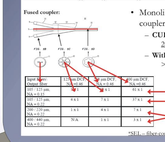
Basic architecture of a monolithic high power fiber laser module



LMA – Large Mode Area Fiber. **CURRENTLY:** 20-μm core in monolithic systems

- Compact
- Reliable
- Robust
- Efficient
- Facilitates modular architecture
- Manufacturing advantage

Monolithic pump multiplexing technology

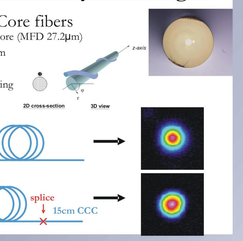


*SEL – fiber coupled single emitter diode

- Monolithic fused couplers:
  - **CURRENTLY:** SM to 20-μm LMA cores
  - **With CCC technology:** >50-μm SM cores

Development of new monolithic technology at University of Michigan

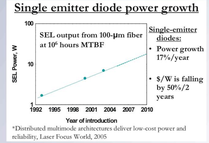
- Chirally Coupled Core fibers
  - 34μm/0.066NA center core (MFD 27.2μm)
  - LP_{01} modal loss: 0.2dB/m
  - 0.16dB splicing loss
  - Can be coiled for packaging



Fiber laser efficiency

	Current	Estimated By 2010
• Diode efficiency	>55%	>65%
• Fiber optical	70-80%	70-80%
• Component losses	80%	90%
Total (wall plug)	30%	>40%

Single emitter diode power growth



Single-emitter diodes:

- Power growth 17%/year
- $/W is falling by 50%/2 years

*Distributed multimode architectures deliver low-cost power and reliability, Laser Focus World, 2005

Lifetime/reliability

	Current	Estimated By 2010
• Diode lifetime (MTBF)	Hours	Hours
– Single emitters	$>10^6$	$>10^6$
– Bars	$>3x10^3$	$>5x10^3$
• Fibers and components	$>3x10^3$	$>5x10^3$

Fiber Laser Cost

	Current (CW)	Estimated By 2010
• Diode cost		
– Single emitters	~40 $/W	10-15$/W*
• 20kW F/L cost structure		
– Pump diodes	(70%) 875k$	<400k$
– Total system	1.3M$	~1M$
• 20kW fiber laser cost		
– Capital cost	~60 $/W	20 – 40 $/W
– Operational cost	~50$/hour	<30 $/hour

*"Battle heats up between bars and single-emitter diodes" Laser Focus World

2007 International EUVL Symposium, October 2007, Sapporo Convention Center, Sapporo, Japan