

# Reverse Engineering the Sun for Solar Cell Research (and More!)

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# Outline

## 1. Introduction

- Properties of solar simulators
- Super-continuum lasers

## 2. Simulator Spectral Shaping

- Liquid crystal system
- Liquid crystal / MEMS system

## 3. Multi-Junction Light Biasing

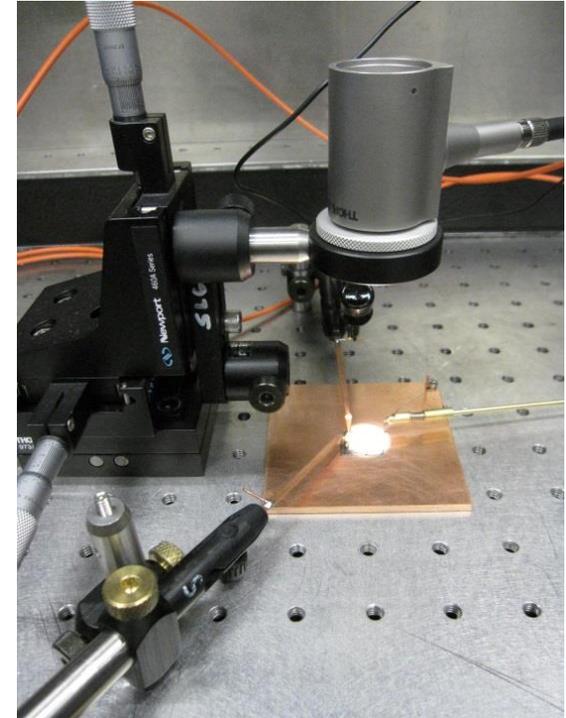
- Junction current limiting

## 4. Multi-Junction Concentrator Cells

- Concentrated irradiance
- Air-mass variations
- Very high irradiance

## 5. Focused White Light Microscopy

## 6. Future Prospects and Conclusion

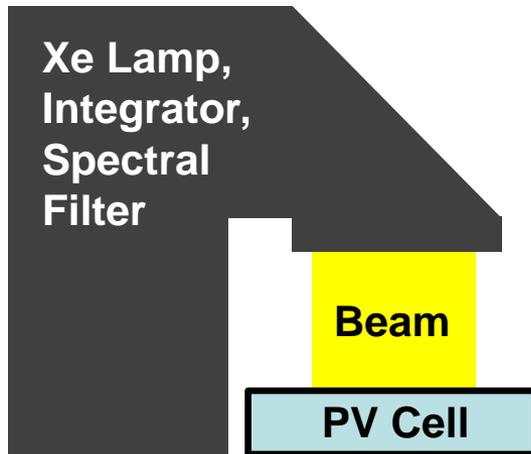


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# 1. Introduction

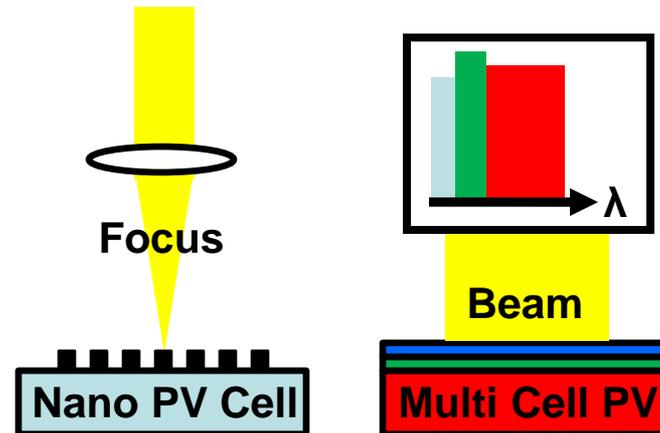
## Types of Solar Simulators

### Conventional Lamp Simulator:



- Lots of power, decent spectral match, good uniformity.
- Spatially incoherent: difficult to focus, collimate, or propagate.
- Typical spectrum not dynamic for multi-junction testing.

### Super-Continuum Simulator:



- Arbitrary, accurate, and rapid spectral shaping for PV cell studies. Diurnal variations.
- Focused spot for micron-scale excitation and imaging ( $< 2 \mu\text{m}$ ).
- Multi-junction light biasing.

# A Super-Continuum (White Light) Laser

## Features and Advantages:

- Power: **> 20 Watts CW**
- Spectrum: **400 to 2400 nm (continuous)**
- Pulsed: **sub-nanosecond**
- Rep Rate: **1 to 80 MHz selectable**
- Beam: **Single spatial mode**
  1. Photonic crystal fiber delivery
  2. Key to accurate spectral shaping
  3. Key to beam control
  4. Enables advanced PV testing

## Challenges:

- Not much content below 425 nm
- Pulsed light source

Single Mode Beam

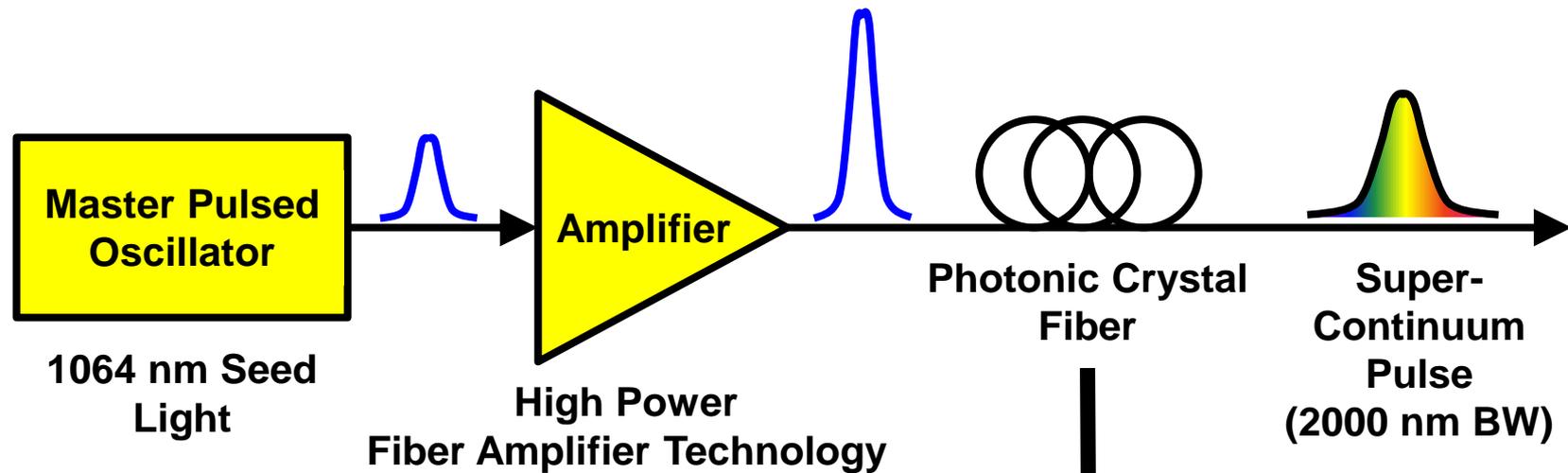


White Light

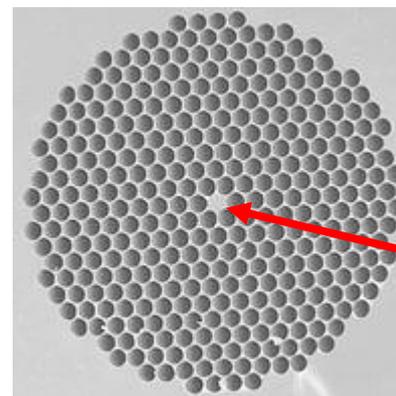


Photo: Fianium Ltd.

# Super-Continuum Laser Topology



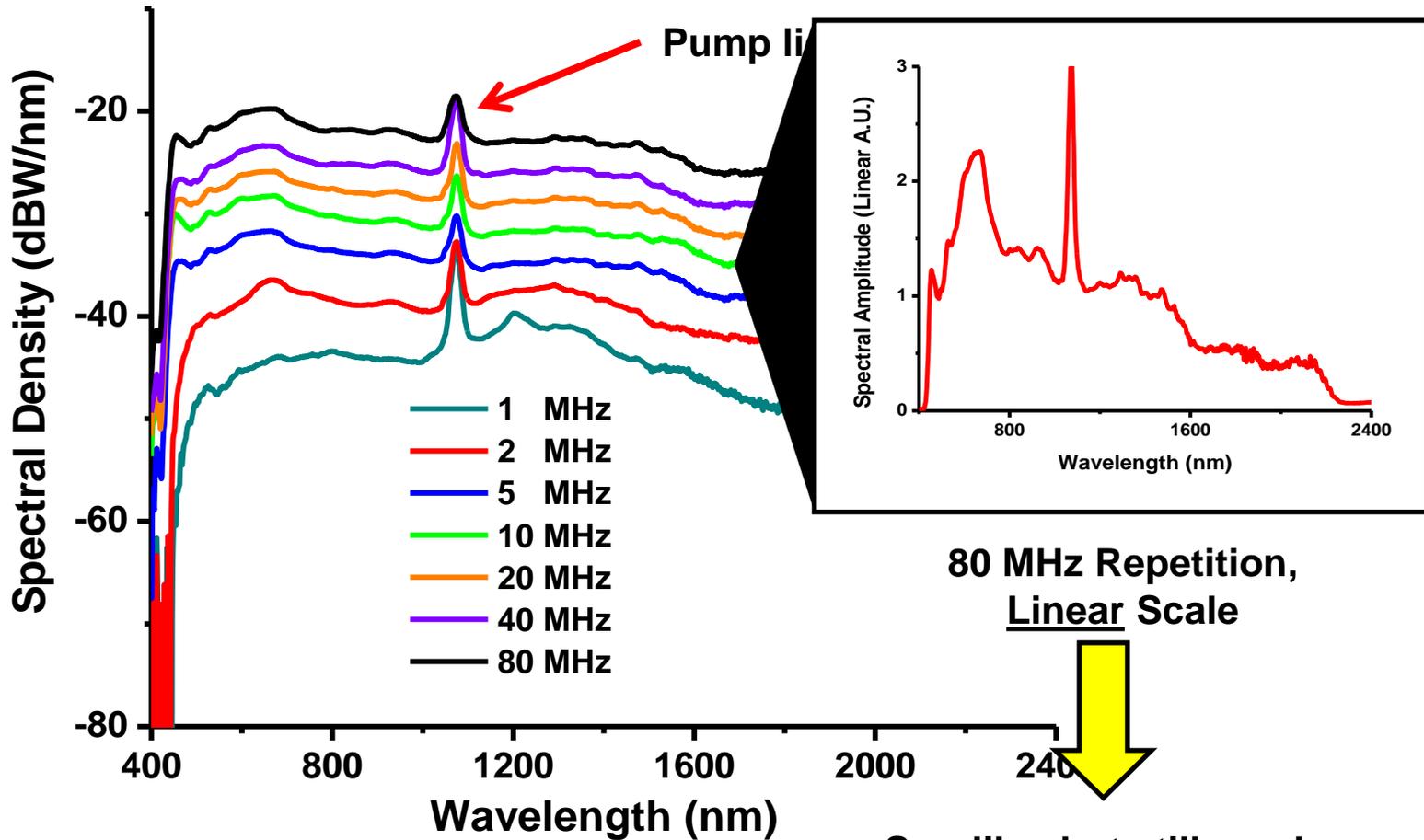
- Endlessly single-mode
- Low dispersion
- High nonlinearities
- Result: spectral broadening



**6 Watts!**  
**~8 MW/cm<sup>2</sup>**

Source: US Nav. Res. Lab.

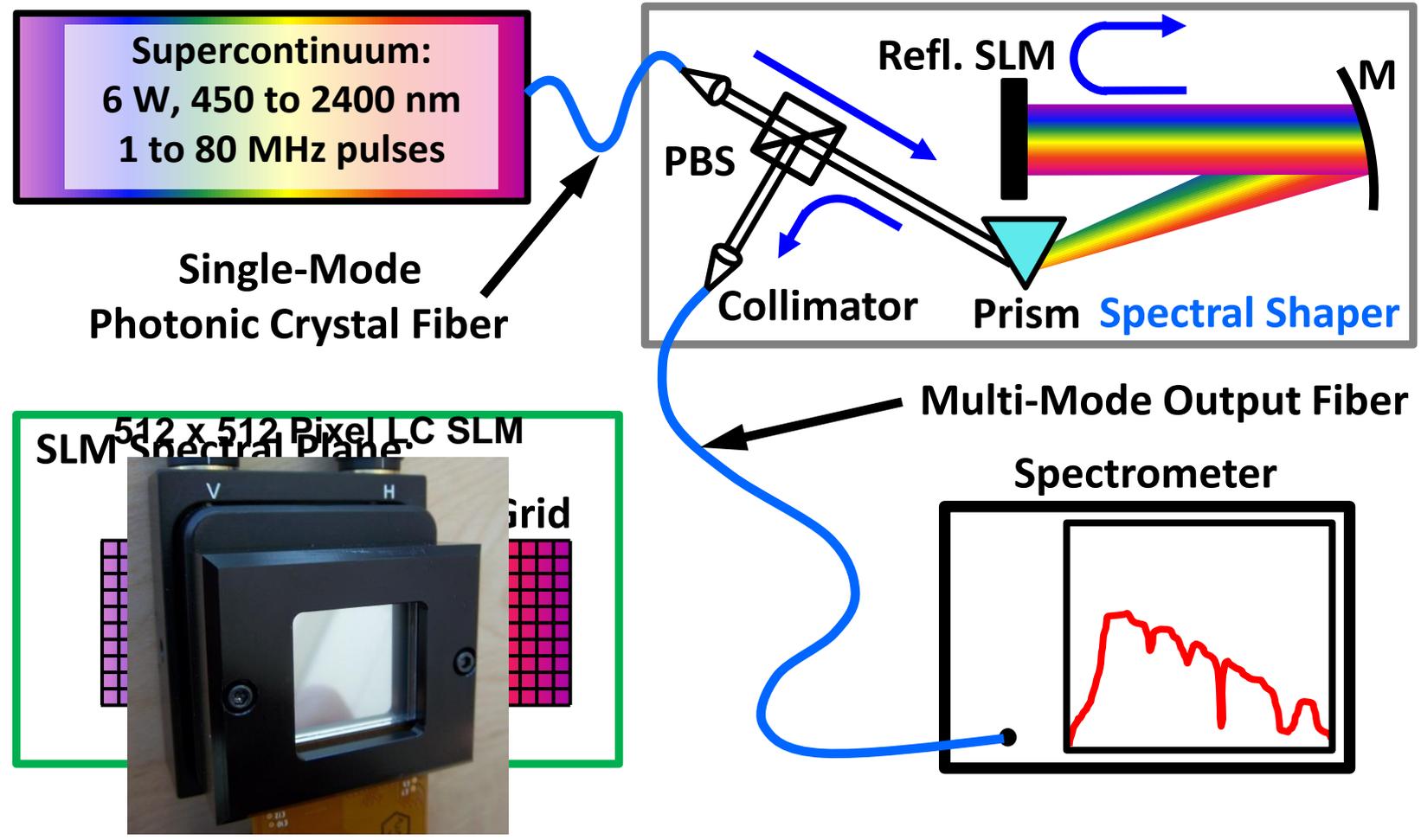
# Super-Continuum Spectra



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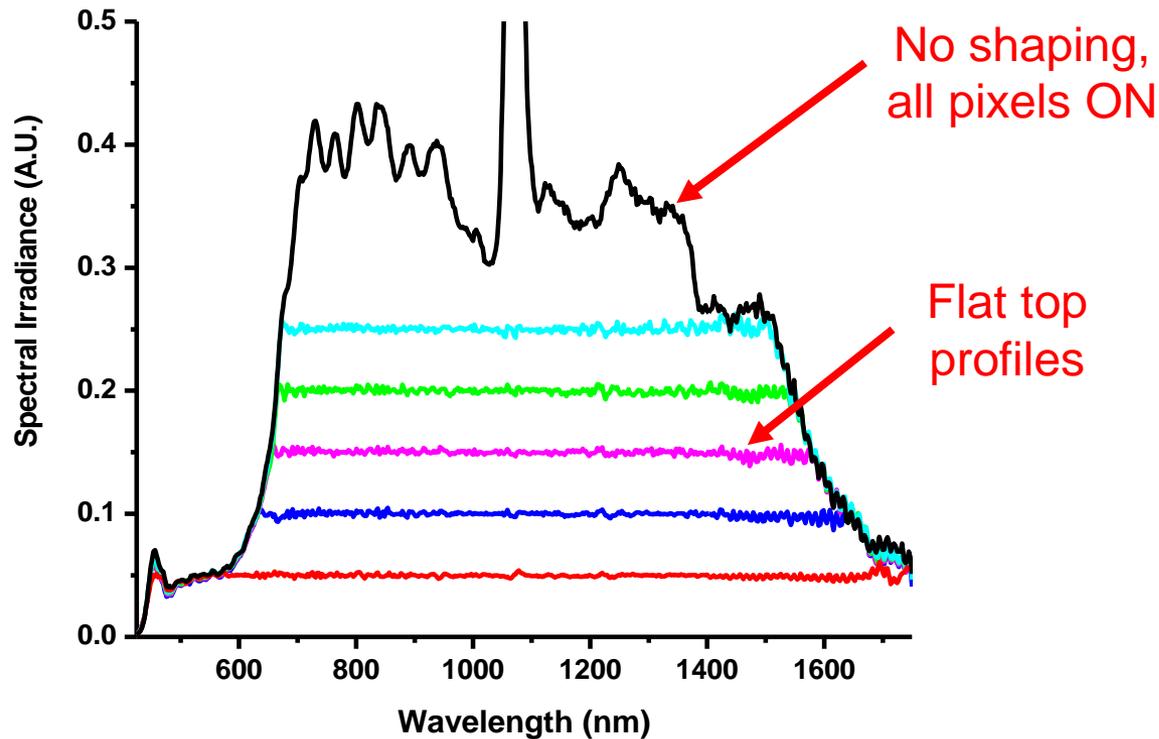
## 2. Simulator Spectral Shaping

# Spectral Shaping with Liquid Crystal SLM



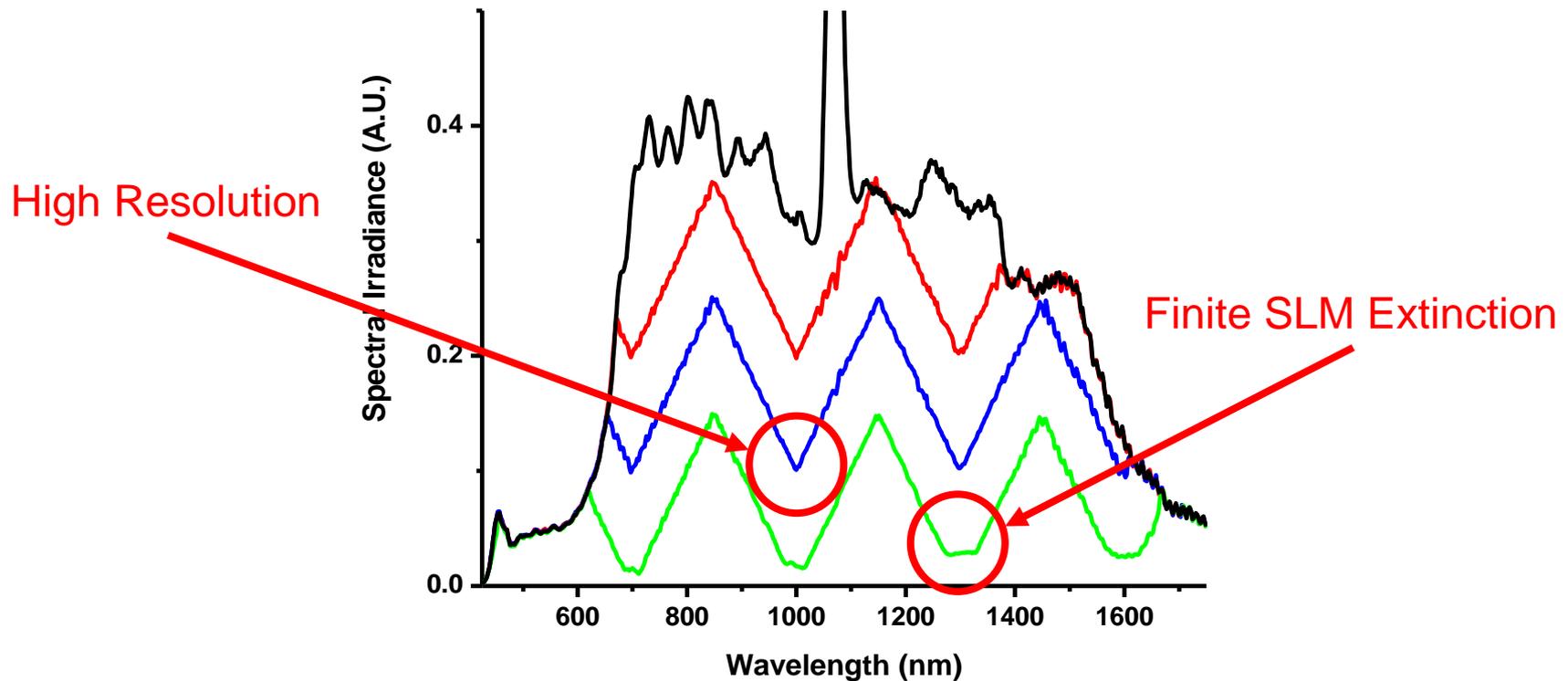
Prism-based spectrometer – like a femtosecond pulse shaper.

## Flat Spectral Shaping



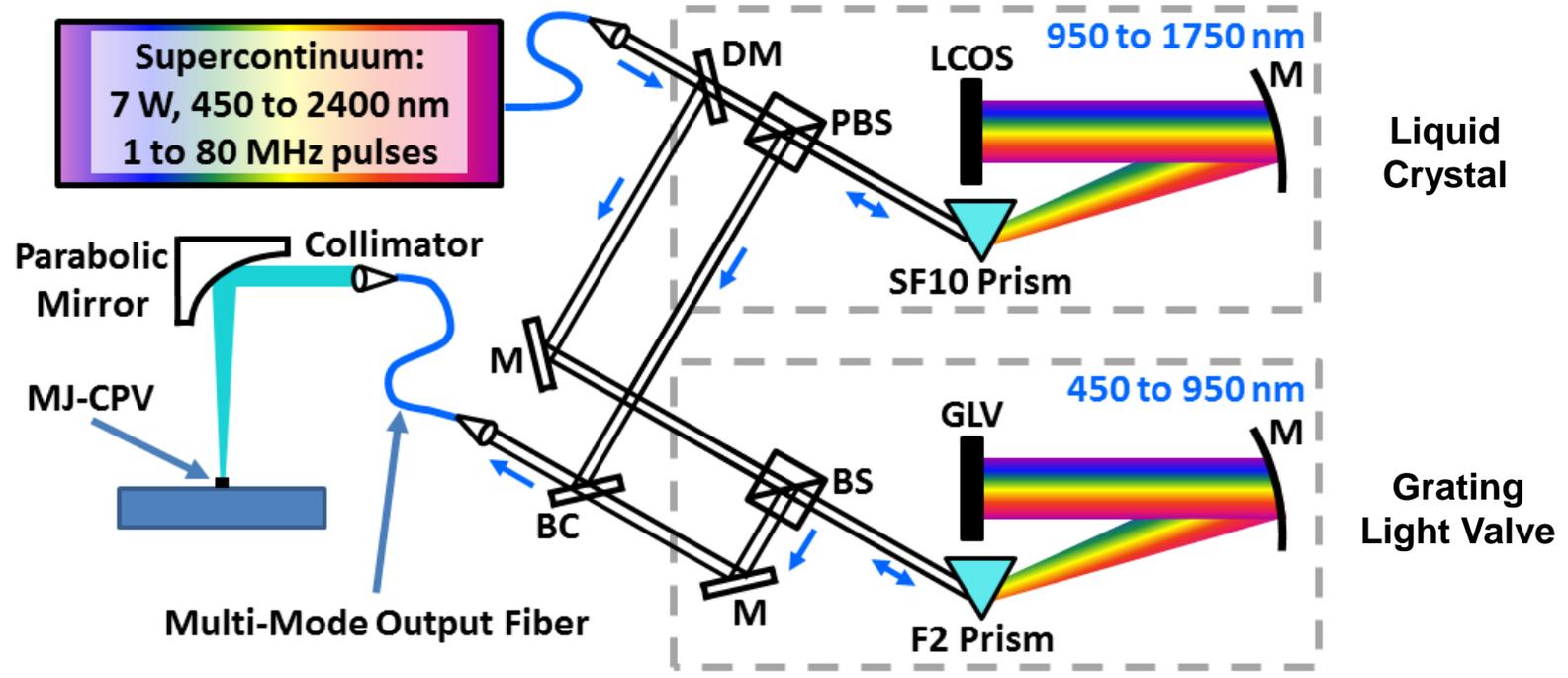
- Flat top independent of irradiance level.
- Iterative method to find optimum SLM drive voltage profiles.
- Profiles can be stored and played rapidly in a sequence.

## Sawtooth Spectral Shaping

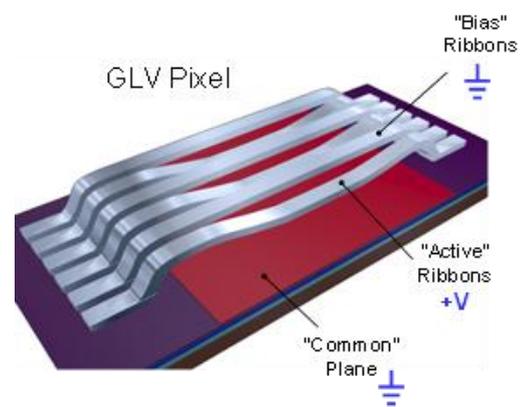


- High resolution: sharp Max and Min
- Finite extinction: Residual SLM birefringence
- But liquid crystals absorb UV, can't handle high power

# Spectral Shaping with Hybrid System

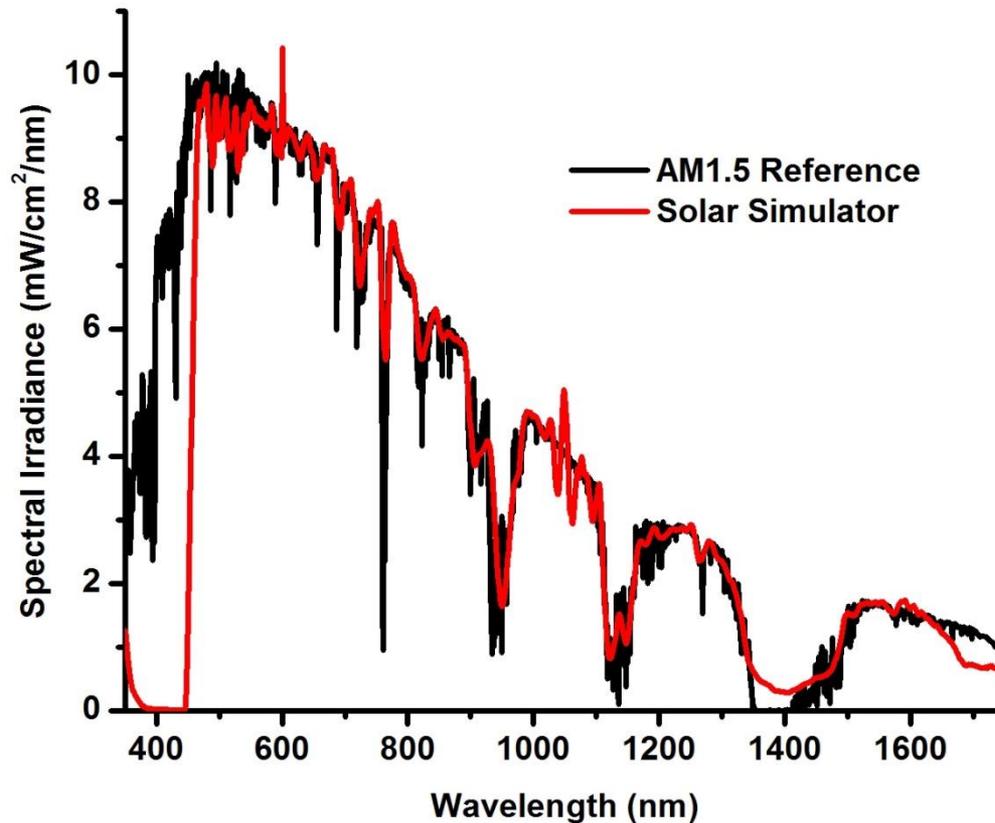


Grating Light Valve (MEMS-based)



- Grating Light Valve (GLV): 450 to 950 nm
- Liquid Crystal SLM (950 to 1750 nm)
- 70 Watt capable

## AM 1.5 Solar Reference Spectrum

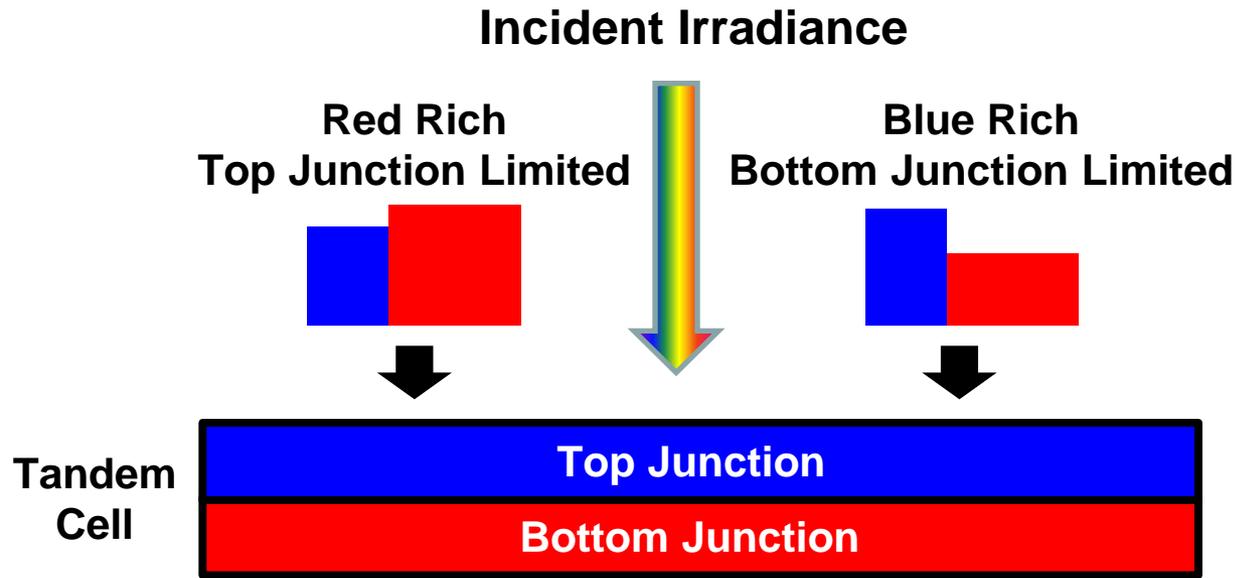


- Excellent spectral match to ASTM G-173-03 at > 450 nm.
- Output: 1 sun over ~ 1 cm<sup>2</sup>
- Finite extinction: degrades at longer wavelengths.

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## 3. Multi-Junction Light Biasing

## Tandem Cell Current Limiting

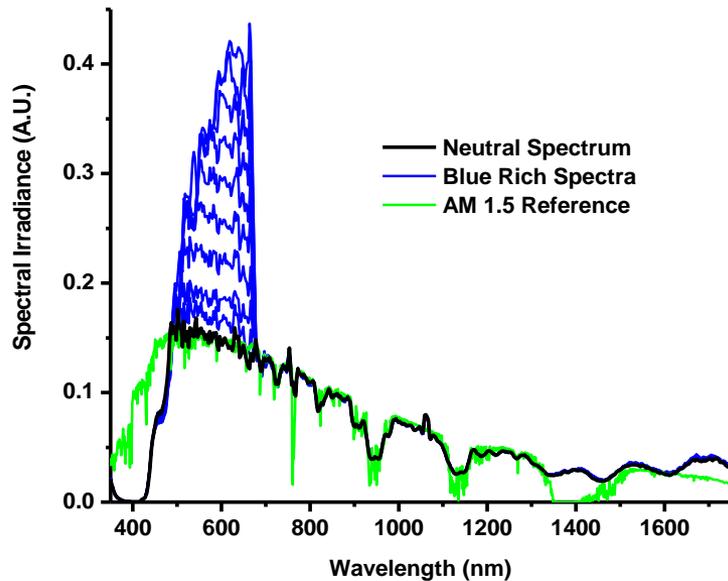


### Tandem Cell Demonstration:

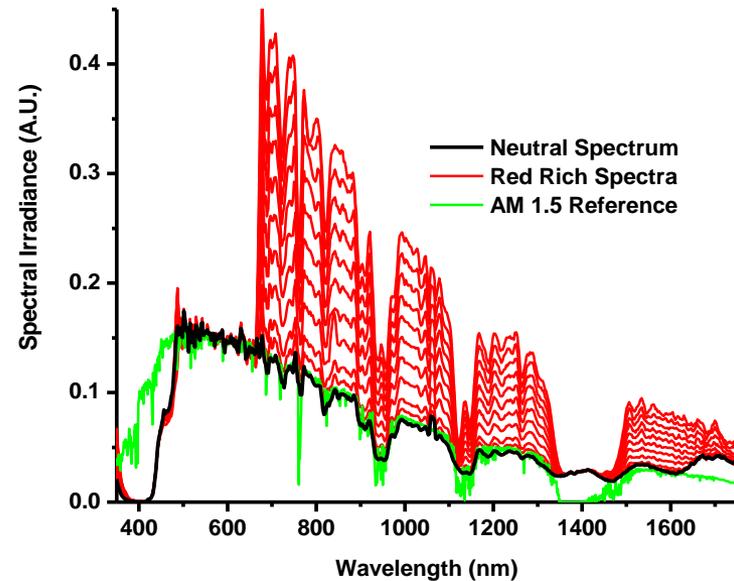
- GaInP/GaAs tandem cell from NREL
- Cell area  $\sim 0.1 \text{ cm}^2$  illuminated at  $\sim 1$  sun
- Crossover wavelength 670 nm

# Tandem Cell Light Biasing Spectra

## Blue-Rich Spectra



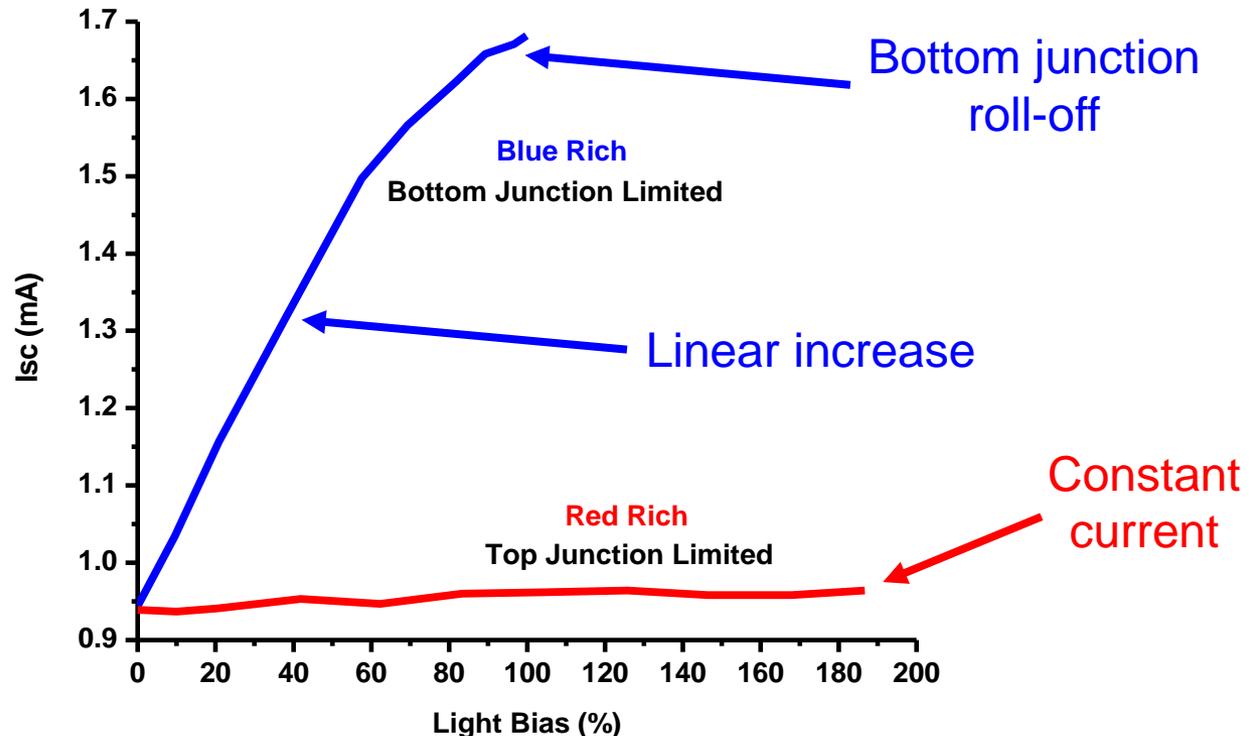
## Red-Rich Spectra



- Increase spectral content above or below 670 nm.
- Hold rest of spectrum constant to AM 1.5.
- Define: Light Bias = percent (%) above neutral spectrum level.

## Tandem Cell Current Measurement

Note: not a very good tandem cell

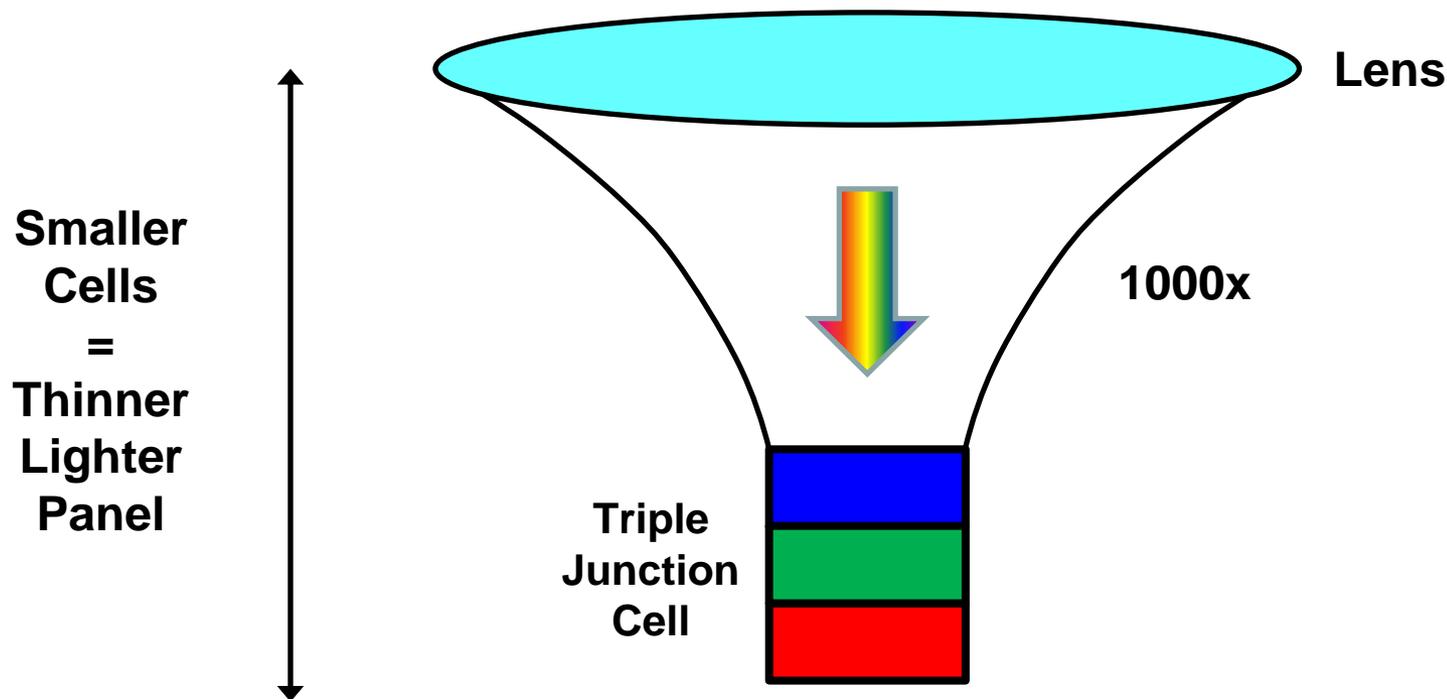


- Full area (0.1 cm<sup>2</sup>) illumination at ~ 1 sun.
- Cell remains at Isc = 0.95 mA despite up to 190% Red light bias.
- Cell current increases with Blue light bias → top junction limited.
- Eventually cell current begins to roll-off due to bottom junction limit.

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## 4. Multi-Junction Concentrator Cells

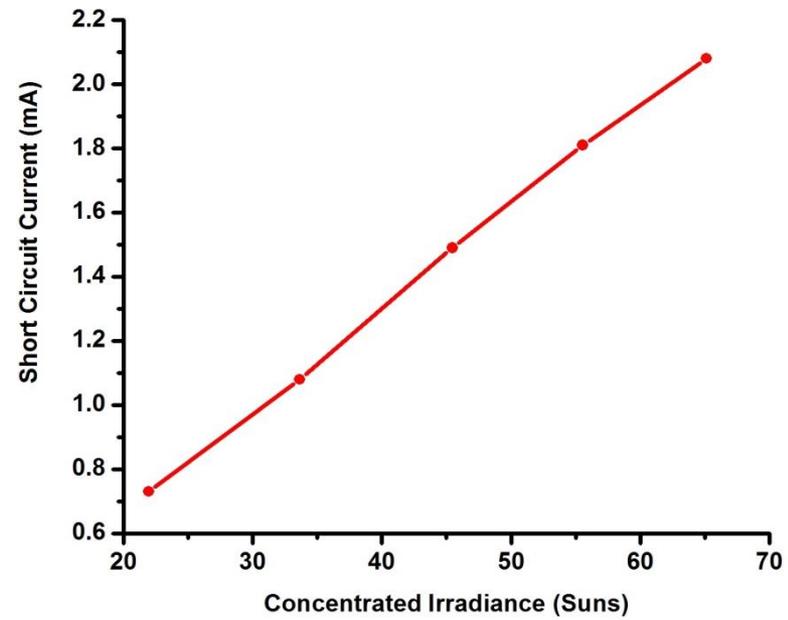
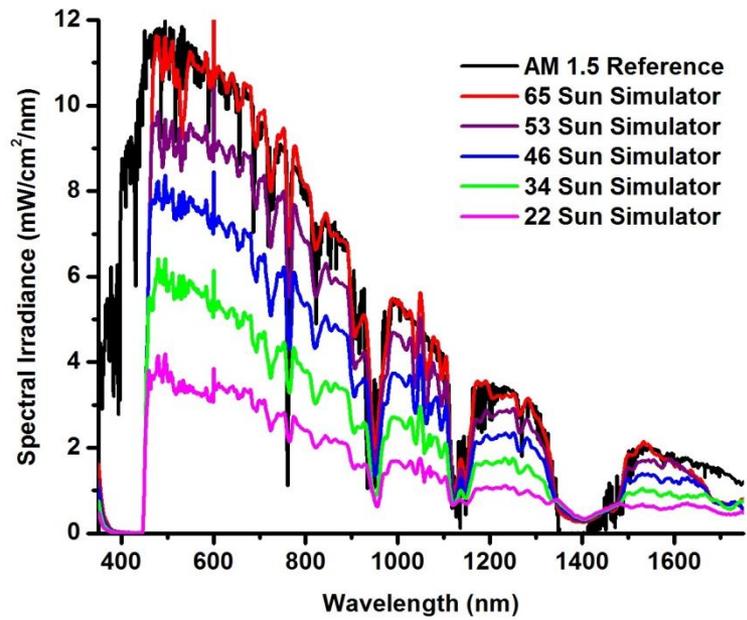
# Multi-Junction Concentrator Photovoltaics



## Commercial micro-area cell:

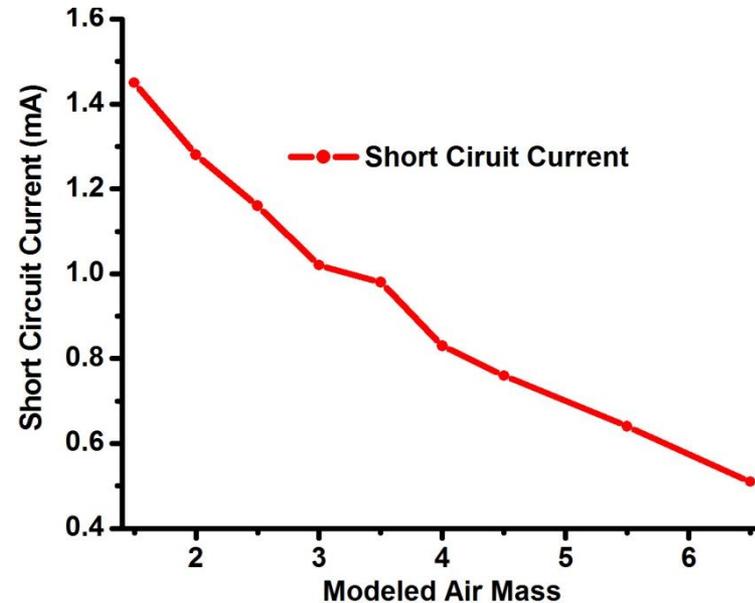
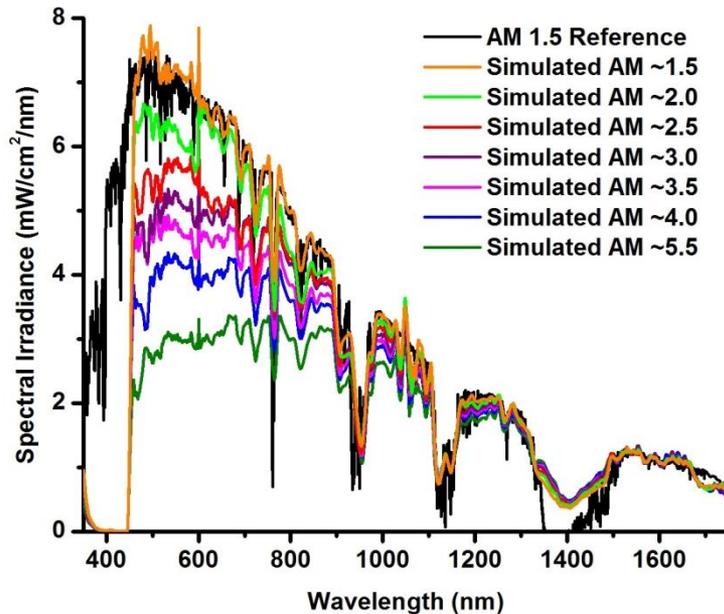
- Triple junction
- 600  $\mu\text{m}$  x 600  $\mu\text{m}$  area
- No lens on sample cells

# Concentrated AM 1.5 Solar Reference Spectra



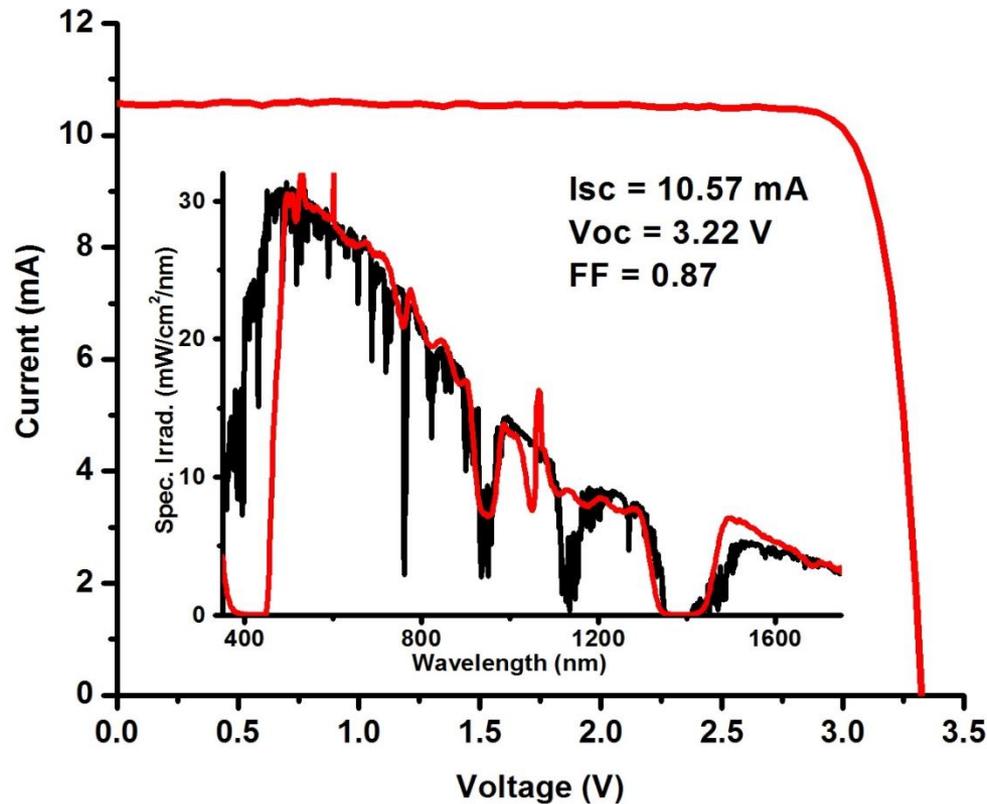
- Programmed spectra; no external attenuator
- Irradiance variation: 22 to 65 suns
- Simulator concentrated to 1.2 mm diameter spot
- Triple cell: linear current dependence

# Atmospheric Attenuation of Solar Spectrum



- Air mass models: time of day, time of year, weather, location
- Top junction sees less light – junction current imbalanced
- Triple-junction cell efficiency decreases with increasing air mass

## 570 Suns Irradiance

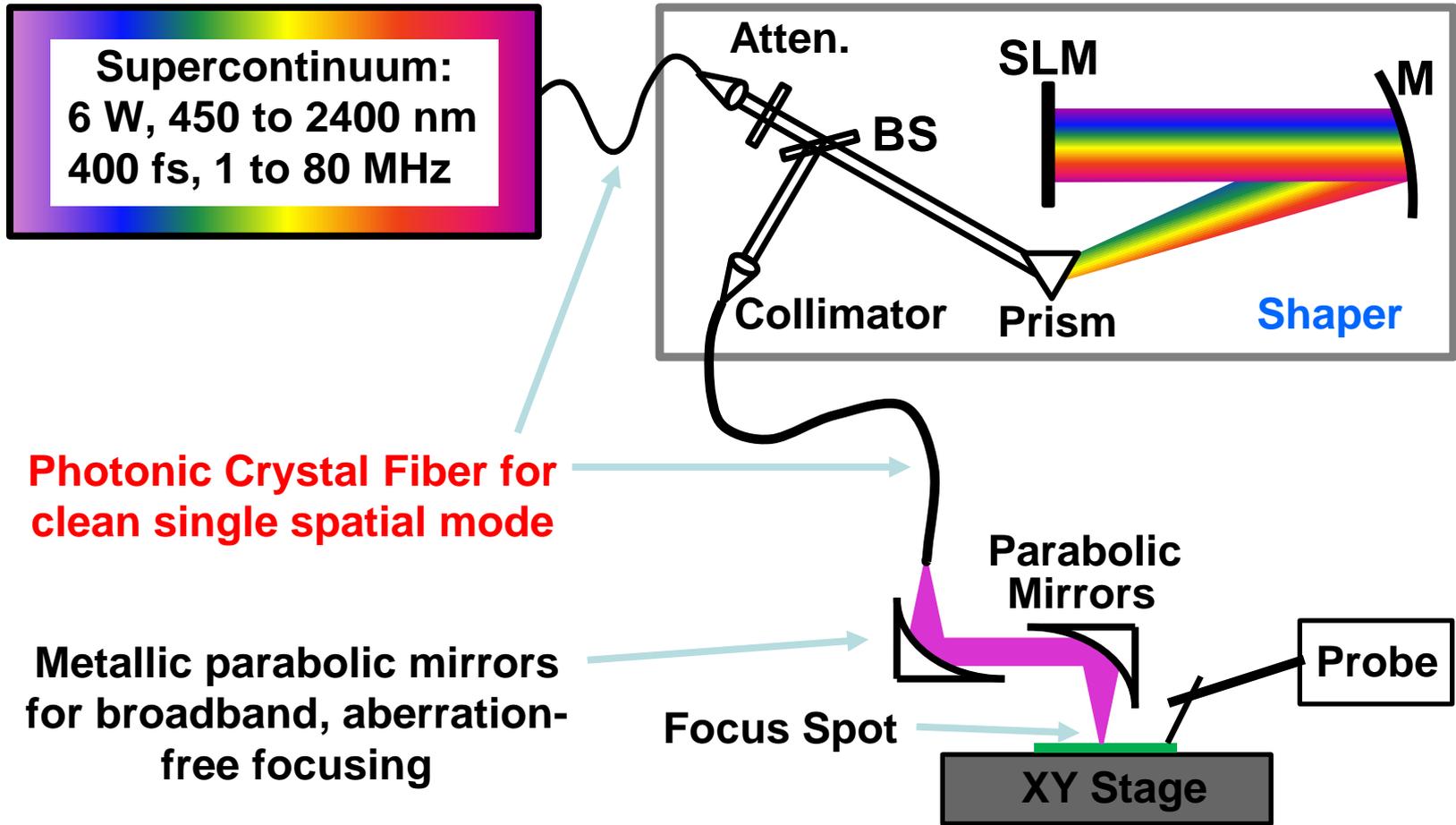


- Used non-programmable spectral shaper – 30% efficiency
- Goal: 1000 or more suns and larger areas

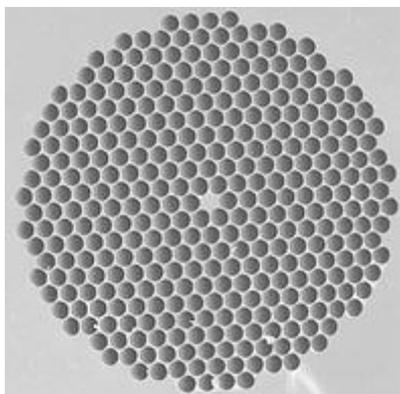
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## 5. Focused White Light

# Parabolic Reflective Focusing



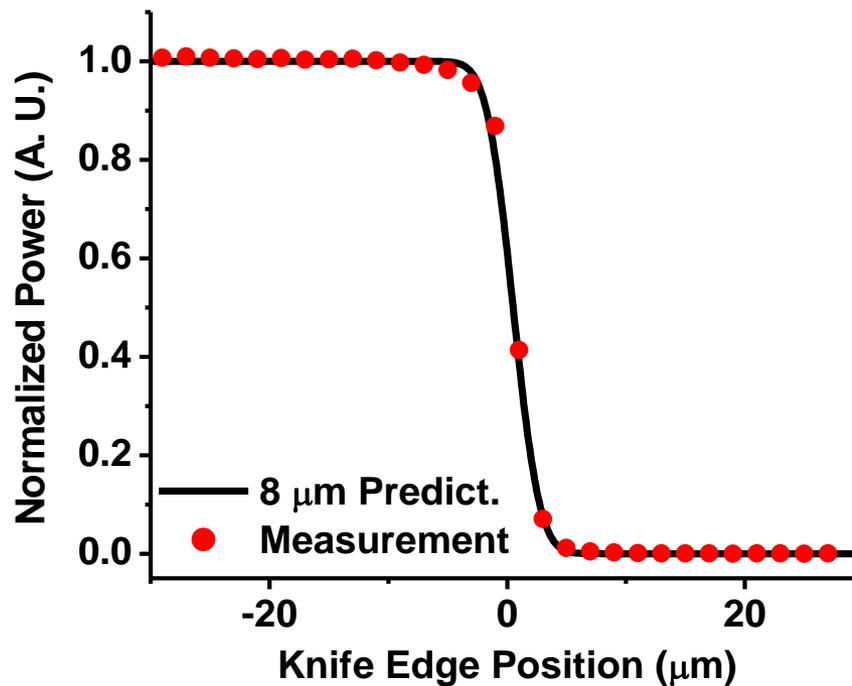
## Quantifying the Focus



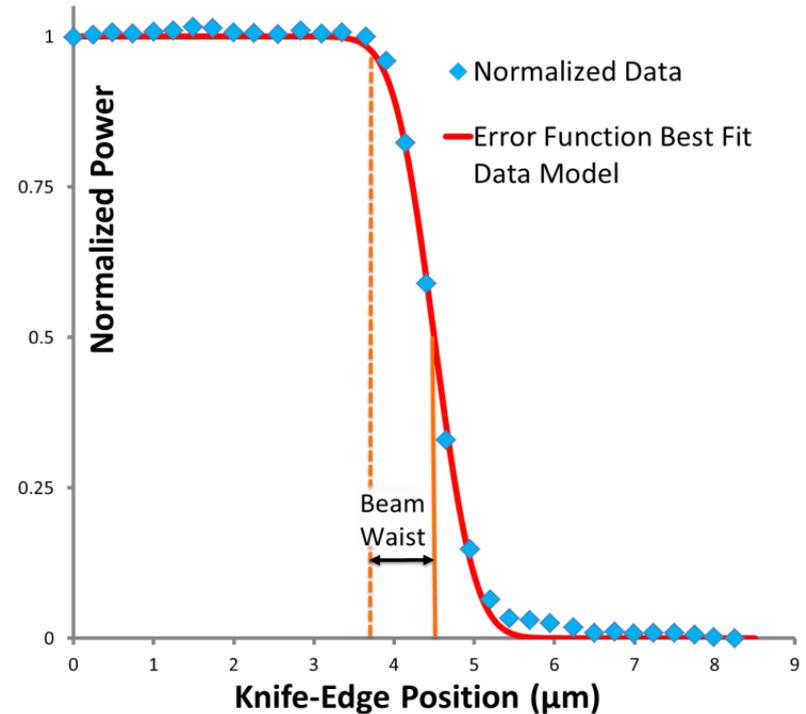
Source: US Nav. Res. Lab

### Scanning Knife Edge Measurement:

White Light Spot: 8  $\mu\text{m}$



# Refractive Focusing



- Multi-element refractive objective (\$20K)
- Amazing broadband coating matches simulator spectrum
- White light spot: **1.3  $\mu\text{m}$ !**

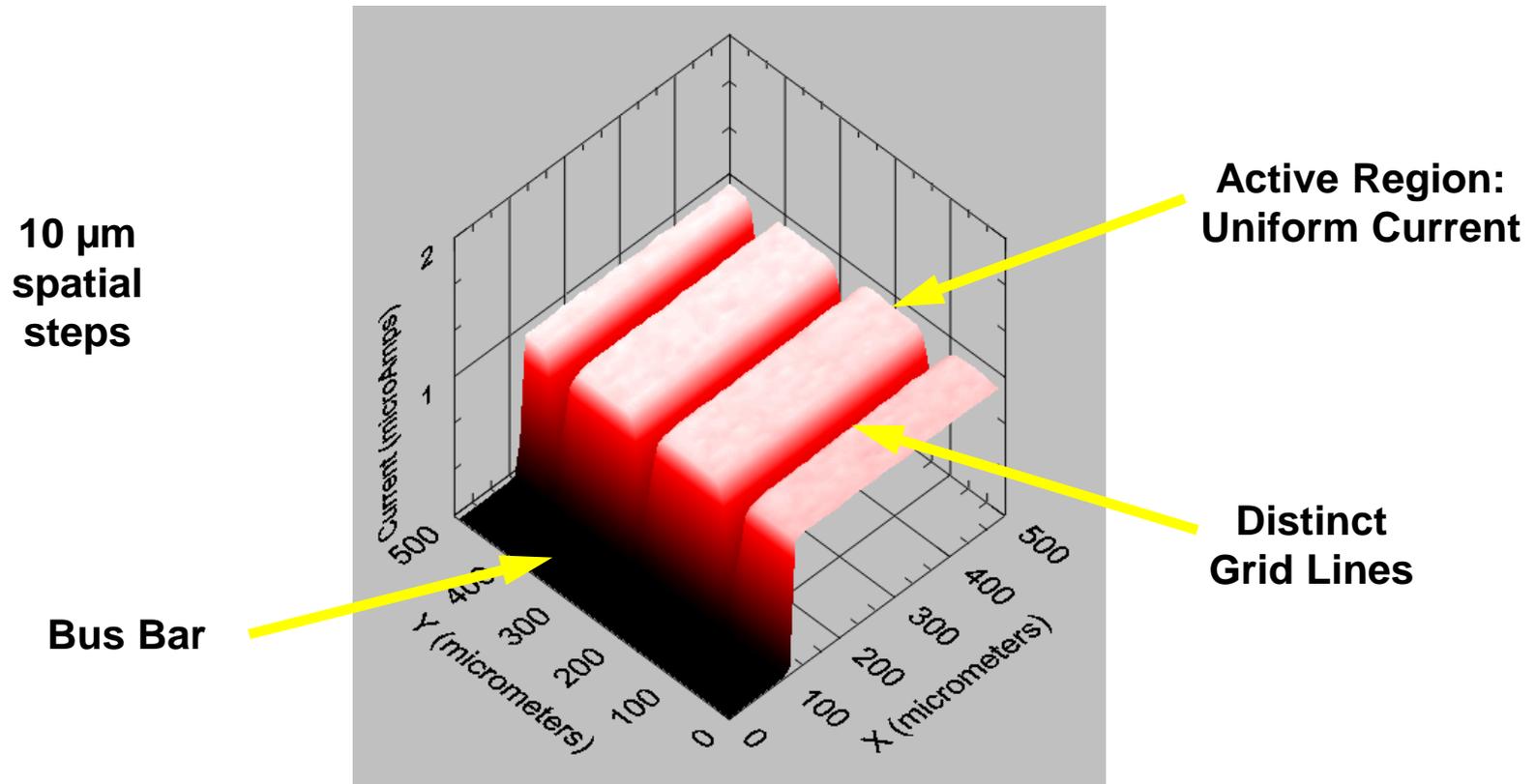
# Full-Spectrum Optical Beam Induced Current

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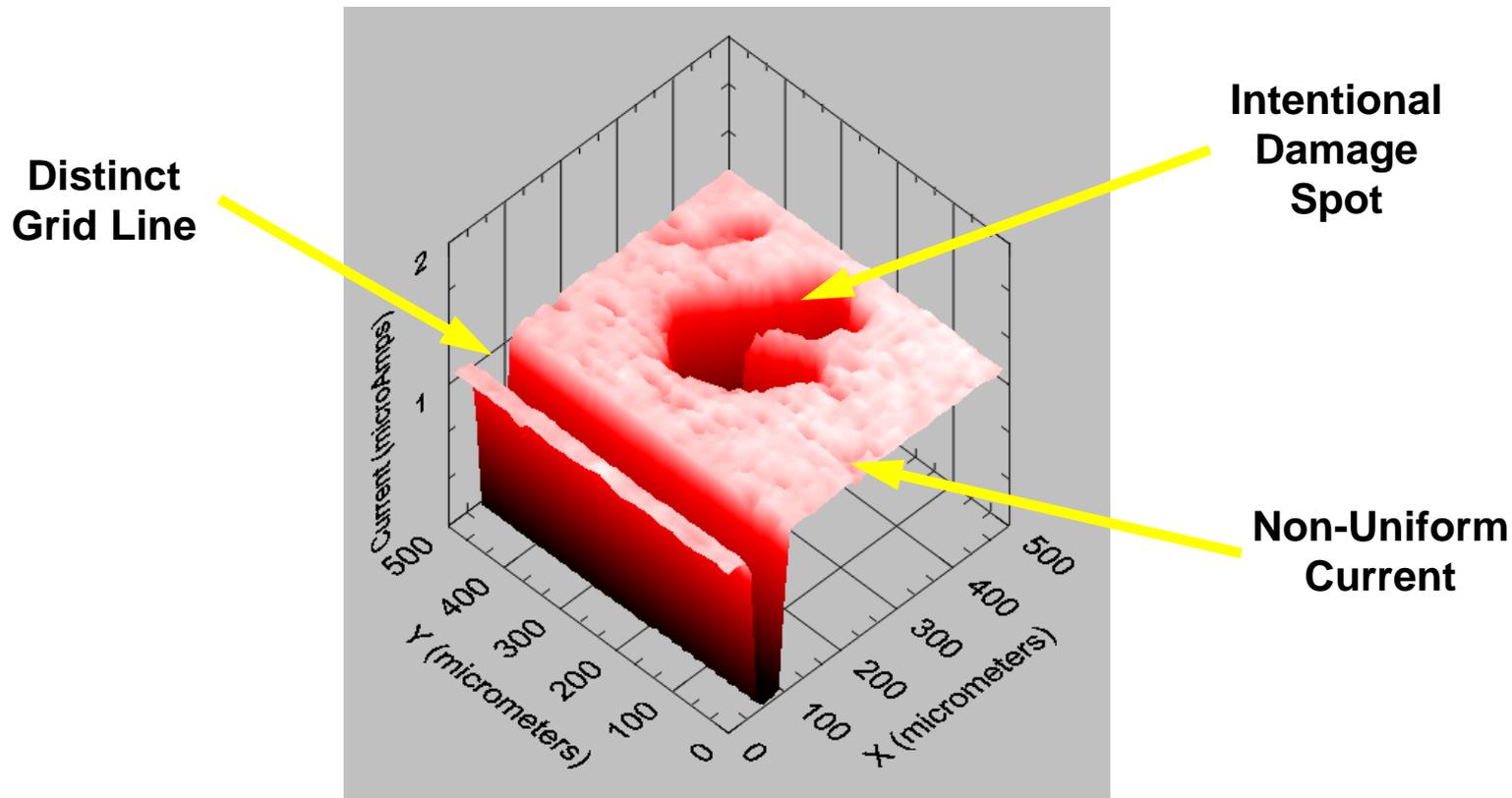
- **FS-OBIC**: uses focused, white-light simulator beam
  - **Not feasible until now – usually narrowband lasers**
  - **Raster-scan across samples**
  - **Monitor short-circuit current**
  - **Multi-sun irradiance; ~160 suns used here**

## FS-OBIC: GaAs Cell



- Bus bar and grid lines are dark – no current
- Image features are distinct
- Crystalline material:  $\sim 1 \mu\text{A}$  uniform current

## FS-OBIC: CIGS Cell



- **Damage:** intentional scratch in deposited film
- **Non uniform current:** film grains and defects
- **Typical CIGS grain clusters:** 10  $\mu\text{m}$  or more

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## 6. Future Prospects and Conclusion

## Future Prospects: Lasers

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- **Power:**
  - 20W lasers available; 100W lasers on the horizon.
- **Spectrum:**
  - Spectrum is generally limited by silica glass (400 to 2400 nm).
  - Now available: SC lasers down to 320 nm, but only 100 mW. Might be sufficient for microscopy.
- **Repetition Rate:**
  - SC lasers at 1 to 20 kHz rep rate available (~100 mW typ.). Some cells may respond differently to low rep rate.
  - SC laser with MHz rep rates are high power
- **Cost:**
  - Rapidly getting cheaper: 10W = \$50K
  - Cheapest: \$9K for a shoebox-size, kHz laser

**Bottom Line: technology is rapidly developing**

## Future Prospects: Spectral Shaping

- Not Fundamentally Limited:

- Using what is commercially available
- A custom device could do everything

- Liquid Crystal SLM:

- + Preserves beam quality
- Slow, custom-made, UV absorption, polarized

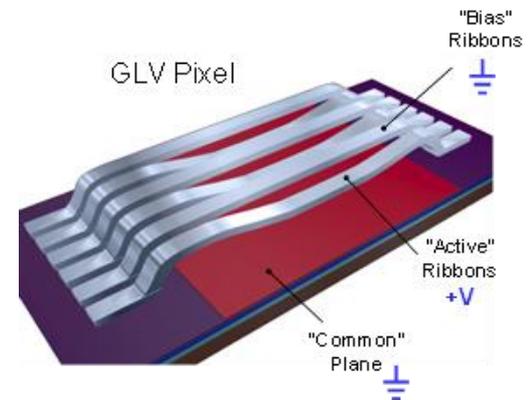
- Grating Light Valve:

- + Broadband reflection, un-polarized, high power, fast
- Not currently available for  $> 1000$  nm

Liquid Crystal  
SLM



Grating Light  
Valve



## Other Application Areas

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- Radiometry
- Responsivity and quantum efficiency
- Hyperspectral imaging sensor calibrations
- Correlation spectroscopy and signature synthesis
- Biomedical imaging – selective fluorescence
- Trace gas detection spectroscopy
- Scattering spectroscopy

## Conclusion

- **Demonstrated a programmable solar simulator for rapid and accurate spectral shaping that looks like the sun.**
  - Arbitrary programmable spectra
  - Applications to light biasing, air-mass variations, FS-OBIC, QE
  - 1 sun over a  $\sim 1 \text{ cm}^2$  area (can be improved)
  - Beam quality: can be focused to  $< 1.3 \mu\text{m}$  spot

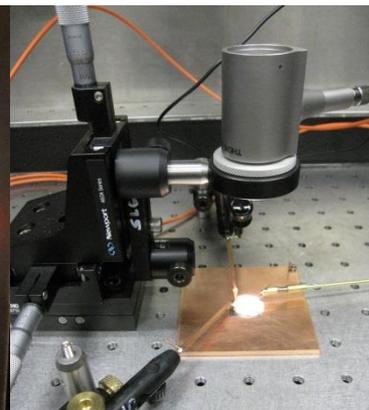
LC SLM



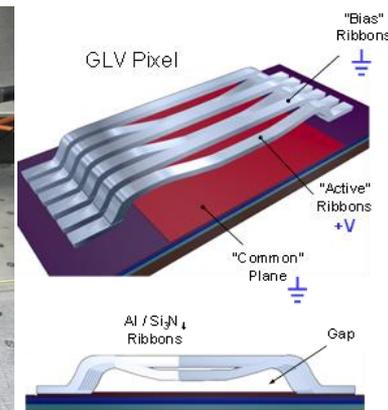
Single Spatial Mode



Collimated Beam



GLV SLM



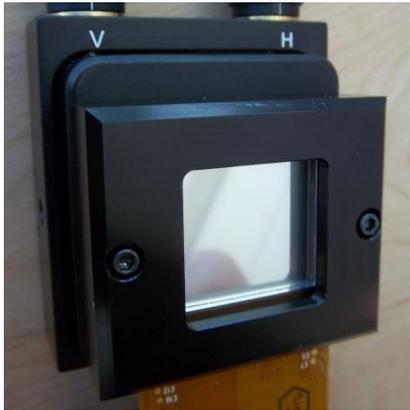
**Questions, collaborations, post-docs: [tasshi@nist.gov](mailto:tasshi@nist.gov)**

## Conclusion

### • Future prospects for:

- Solar simulation with zero spectral error
- Quantum efficiency measurements with pixel modulation
- Nanoscale tip-launch selective solar illumination
- Integration into solar cell production lines
- Commercialization

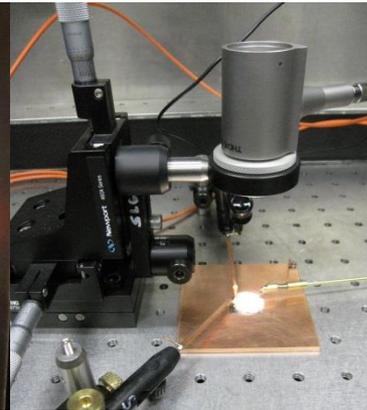
LC SLM



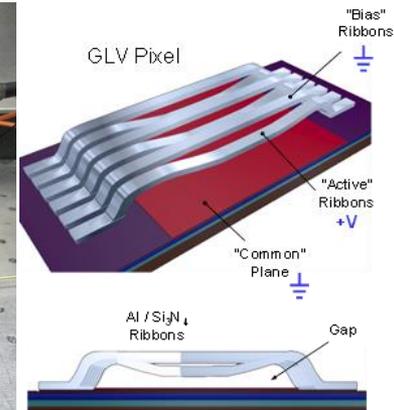
Single Spatial Mode



Collimated Beam



GLV SLM



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