

UV metrology for controlling and charactering the vat photopolymerization (VP) process

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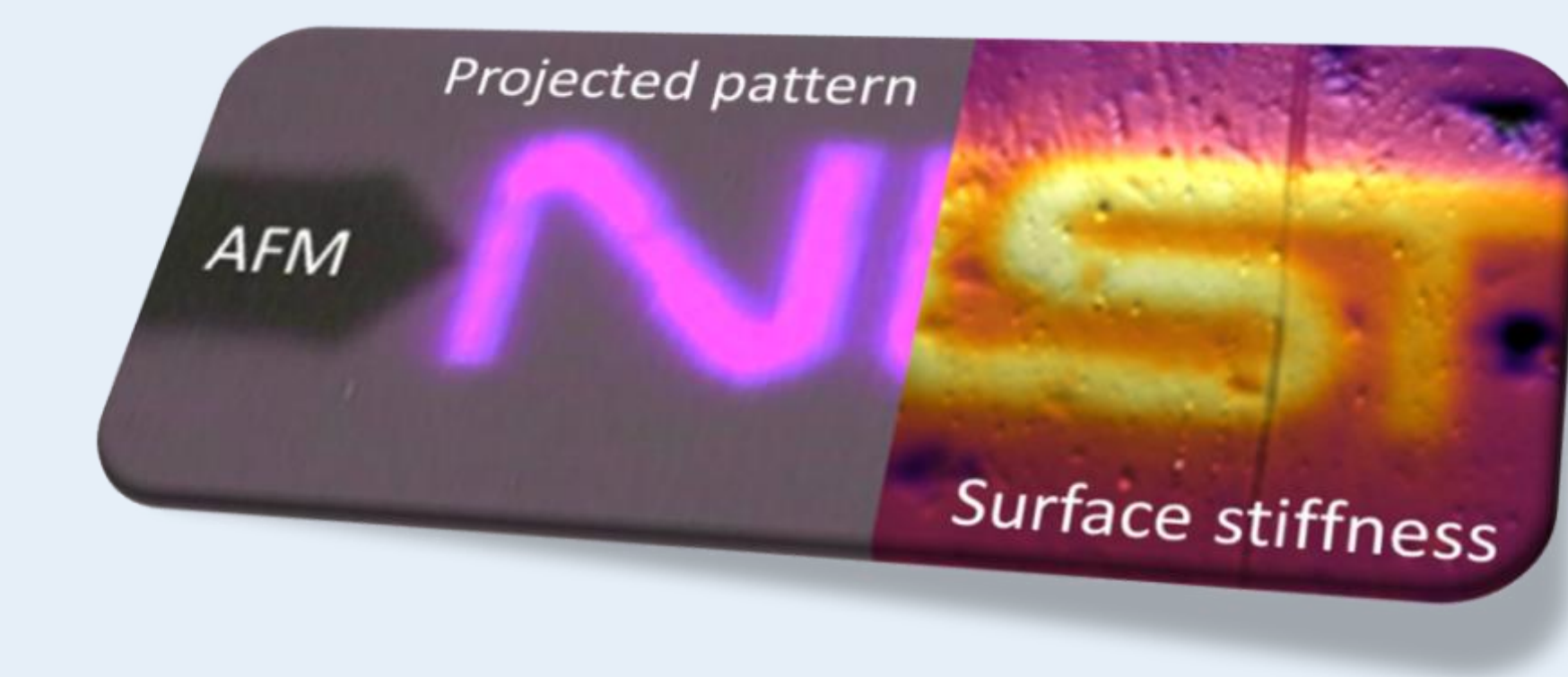
National Institute of Standards & Technology, USA

Collaborating for Impact Now (CoIN)

The CoIN Program was established to bring together researchers across technical fields to work on high-value projects. One such project aims to address imperfections in light engines that can lead to inconsistencies in material properties, geometric discrepancies, and print failures.

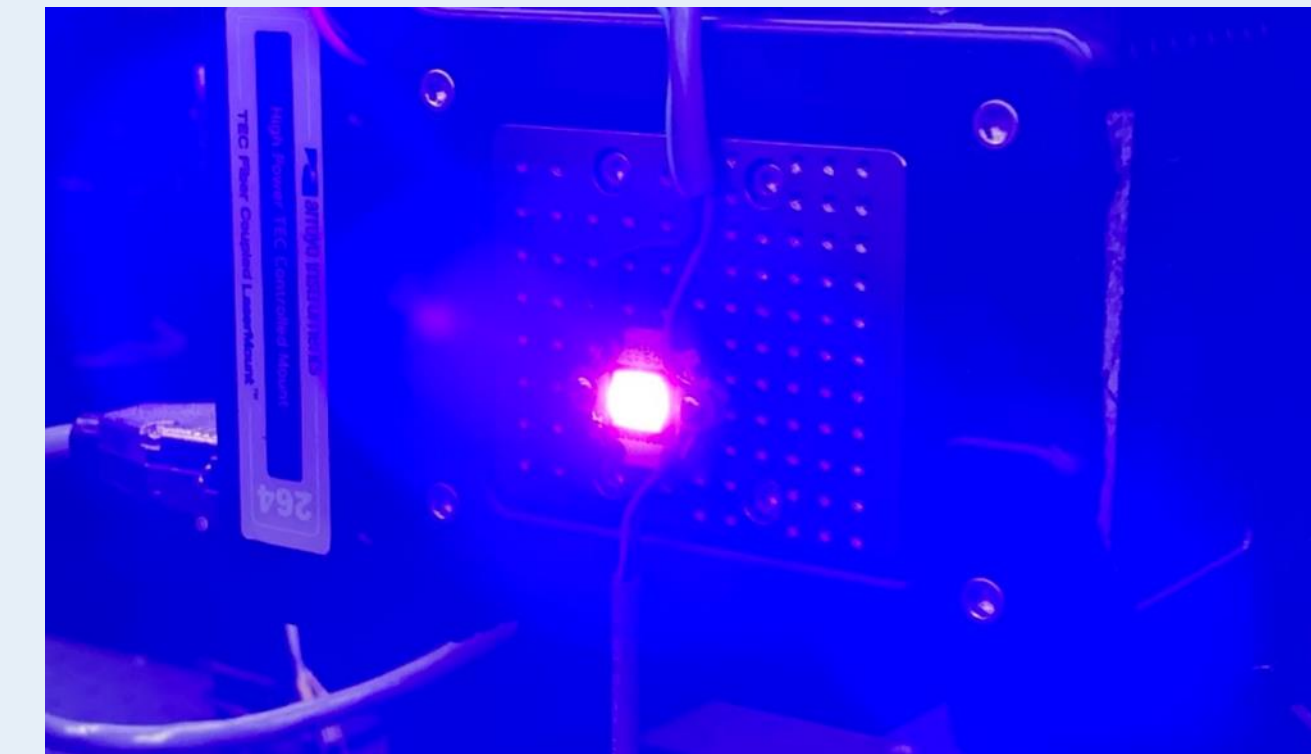
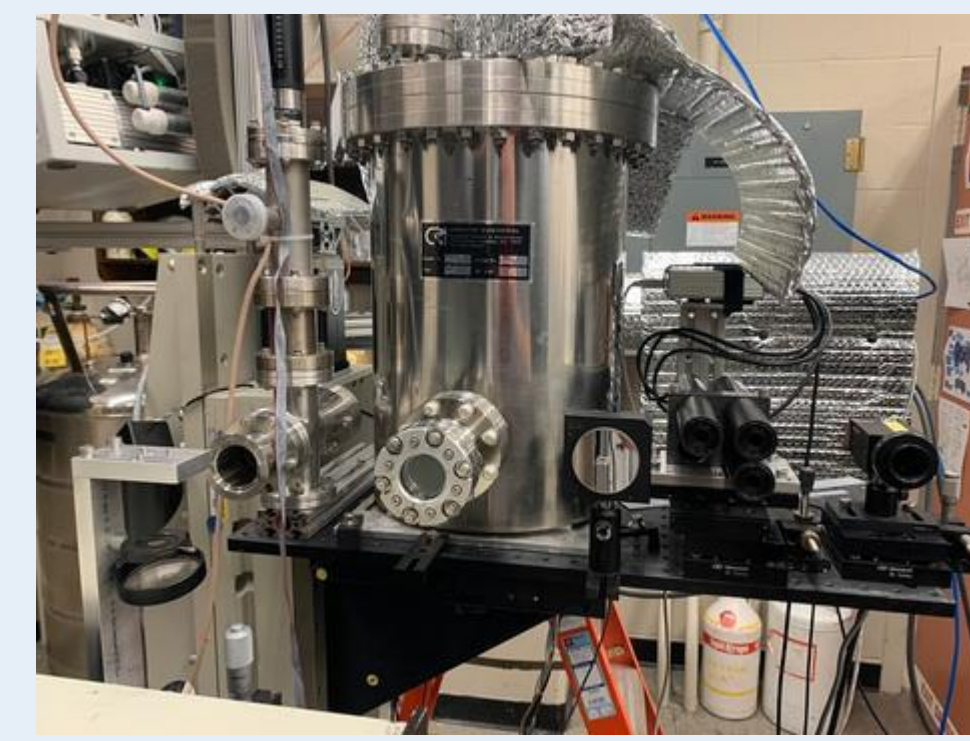
Optical Radiation Group – Sensor Science Division

Mission is to maintain, improve, and disseminate the Nation's radiometric and photometric scales for the measurement of optical radiation which includes ultraviolet (UV) and extreme-ultraviolet (EUV) radiometry.



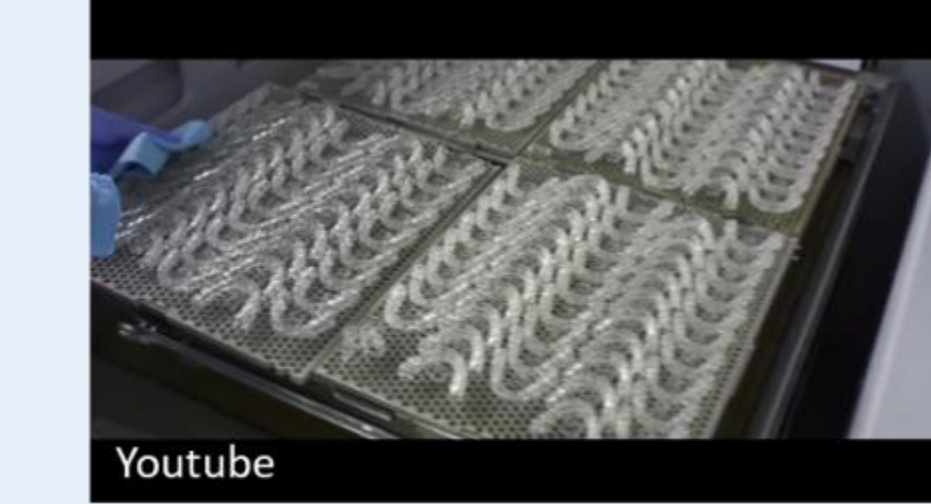
Nanoscale Reliability Group – Applied Chemicals and Materials Division

Mission to develop and disseminate science, standards, and technology for high-resolution measurements of material structure, chemistry, and physical properties, to ensure reliability of materials and devices with critical dimensions in the micrometer to nanometer regime.



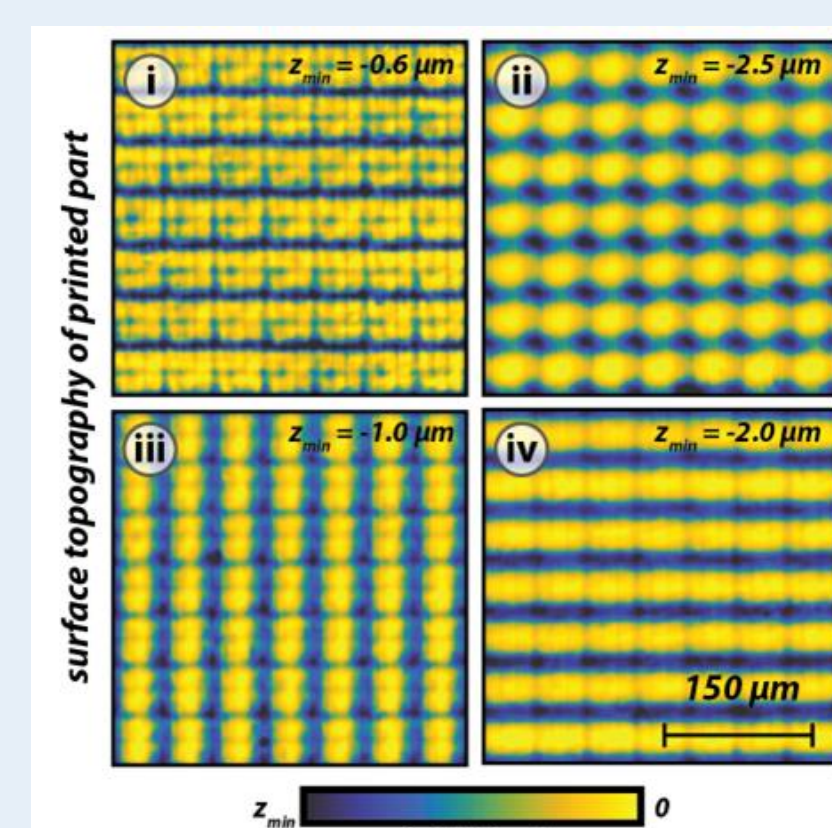
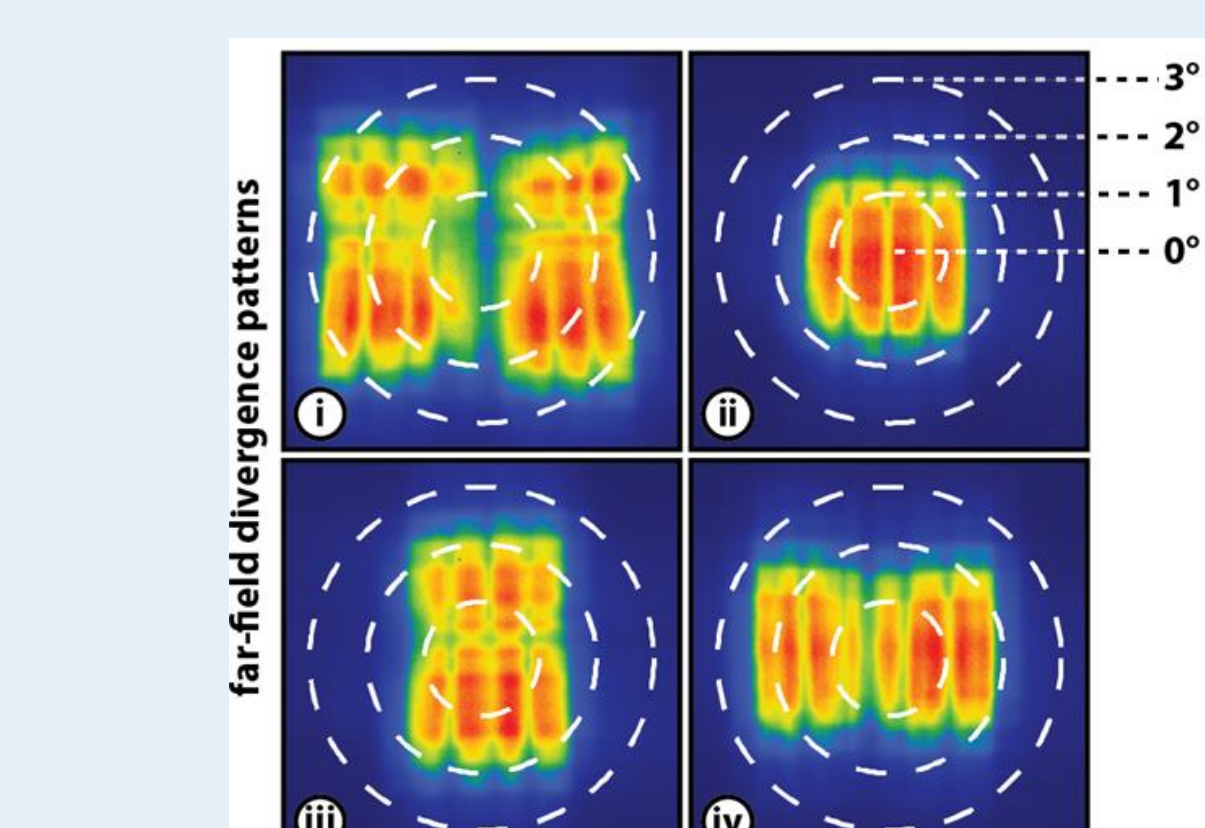
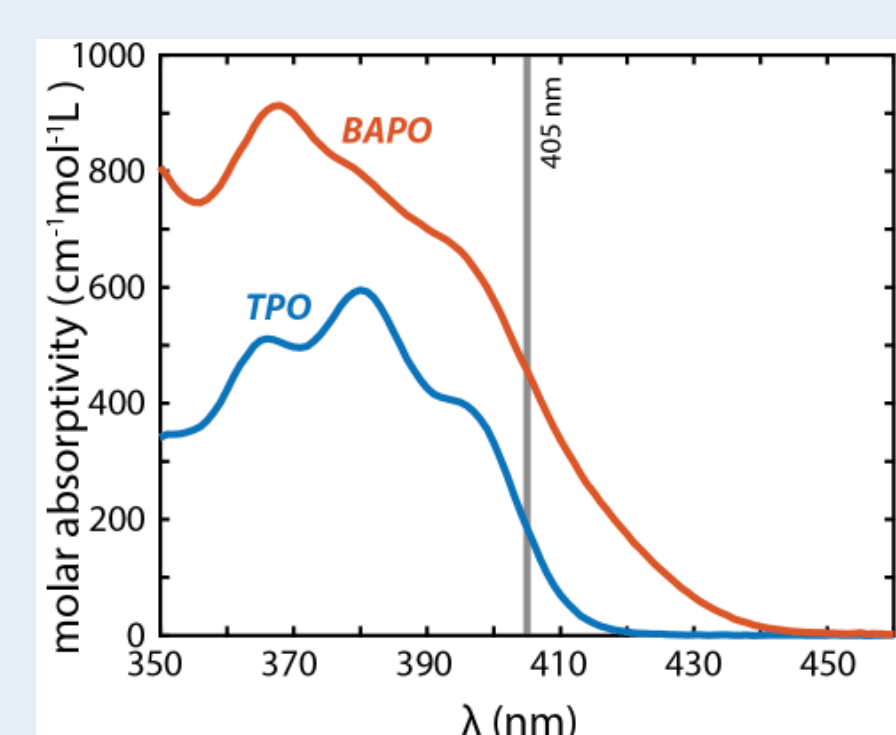
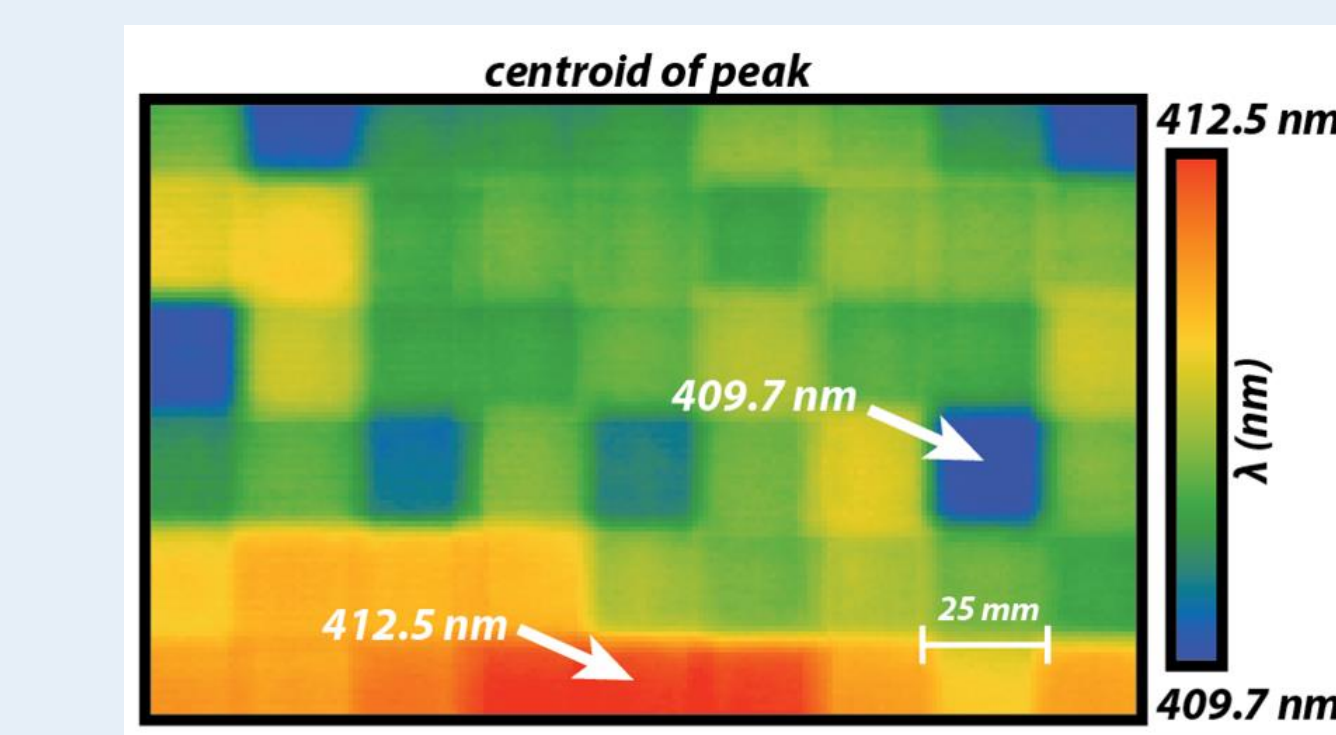
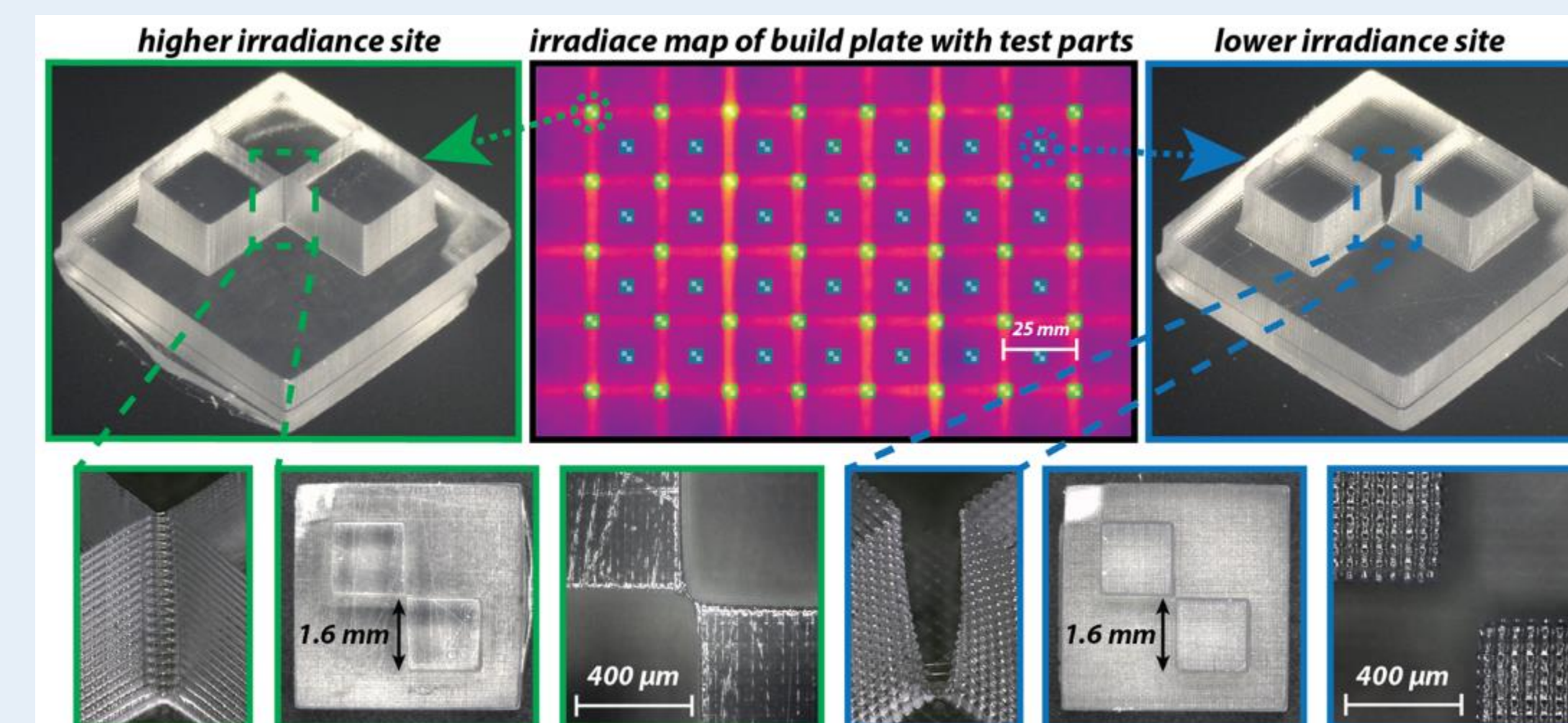
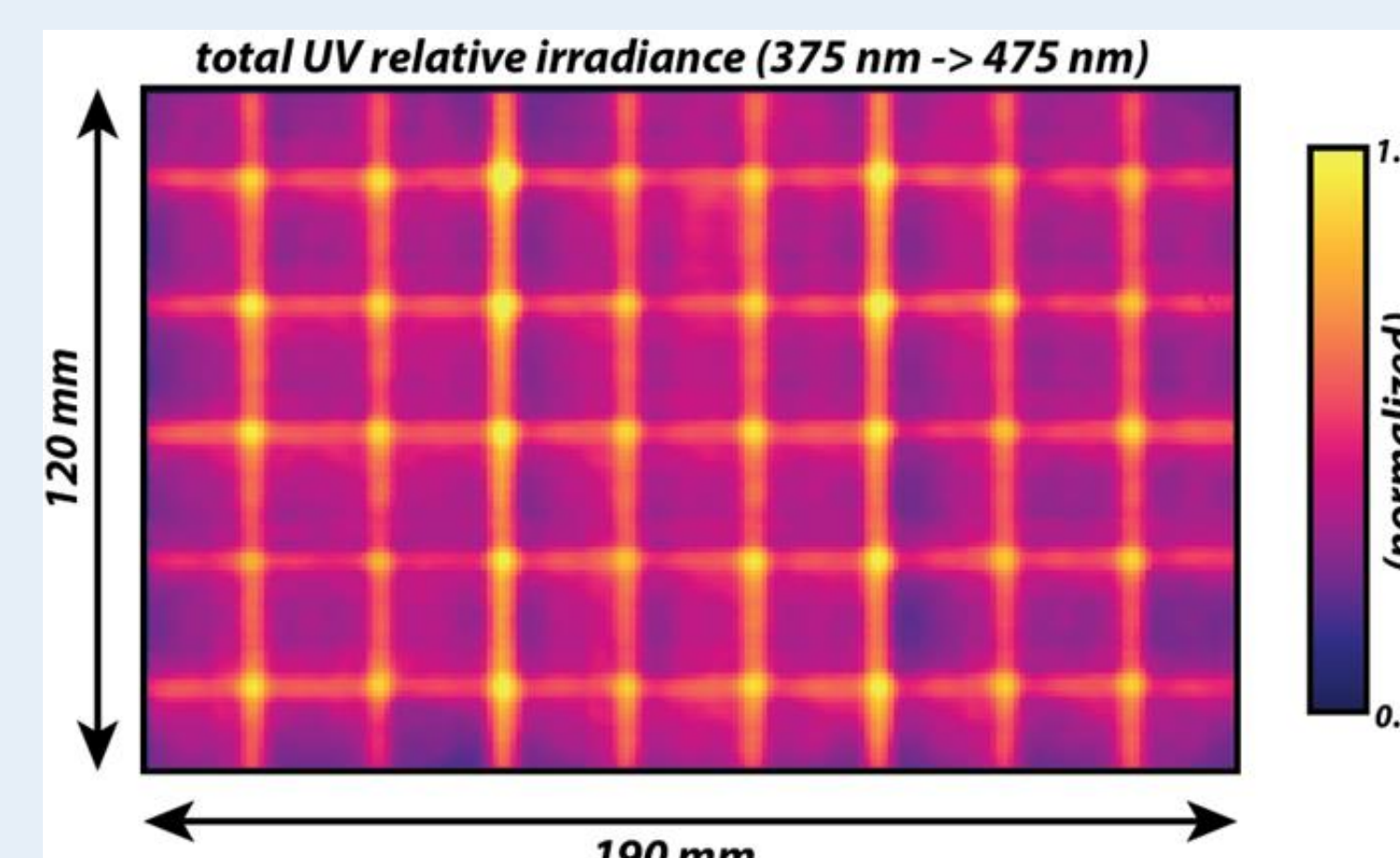
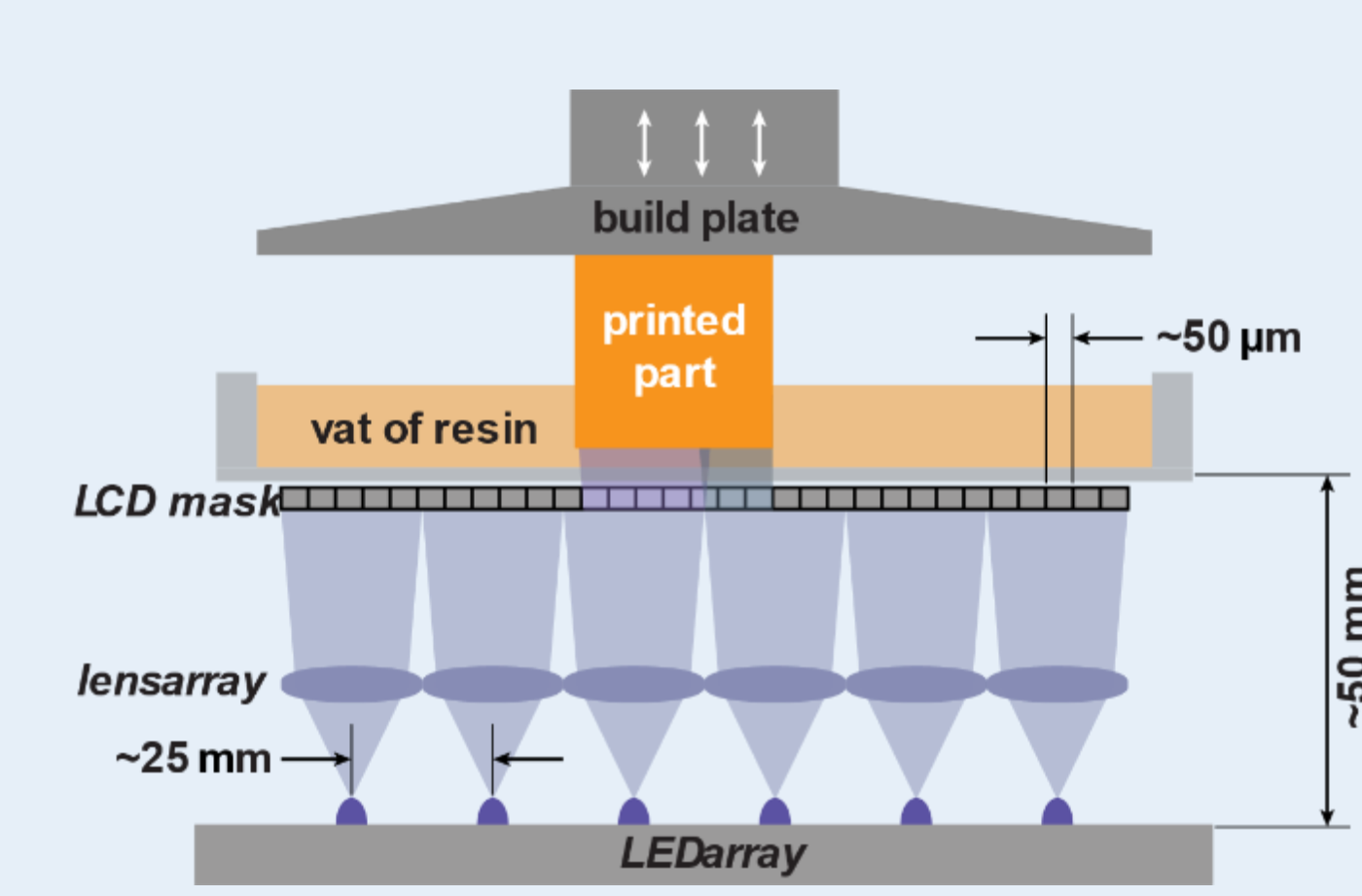
Vat Photopolymerization

A layer of photo-curable liquid resin is selectively cured by light. 3D parts are produced by repeatedly stacking layers.



VP process involves a complex interplay of disciplines, including optical physics, polymer formulation, photopolymerization kinetics (involving thermal, chemical, and material property gradients in time and space), and mechanical engineering.

Typical Light Engines for Vat Photopolymerization Printing



Irradiance heterogeneity is significant! Factor of 3 across build plate

- Gives rise to changes in overall part geometry, can be relatively easily fixed via digital mask

Wavelength heterogeneity is notable. 5 nm across build plate

- Likely causes differences in photopolymer degree of cure, cannot be fixed by user

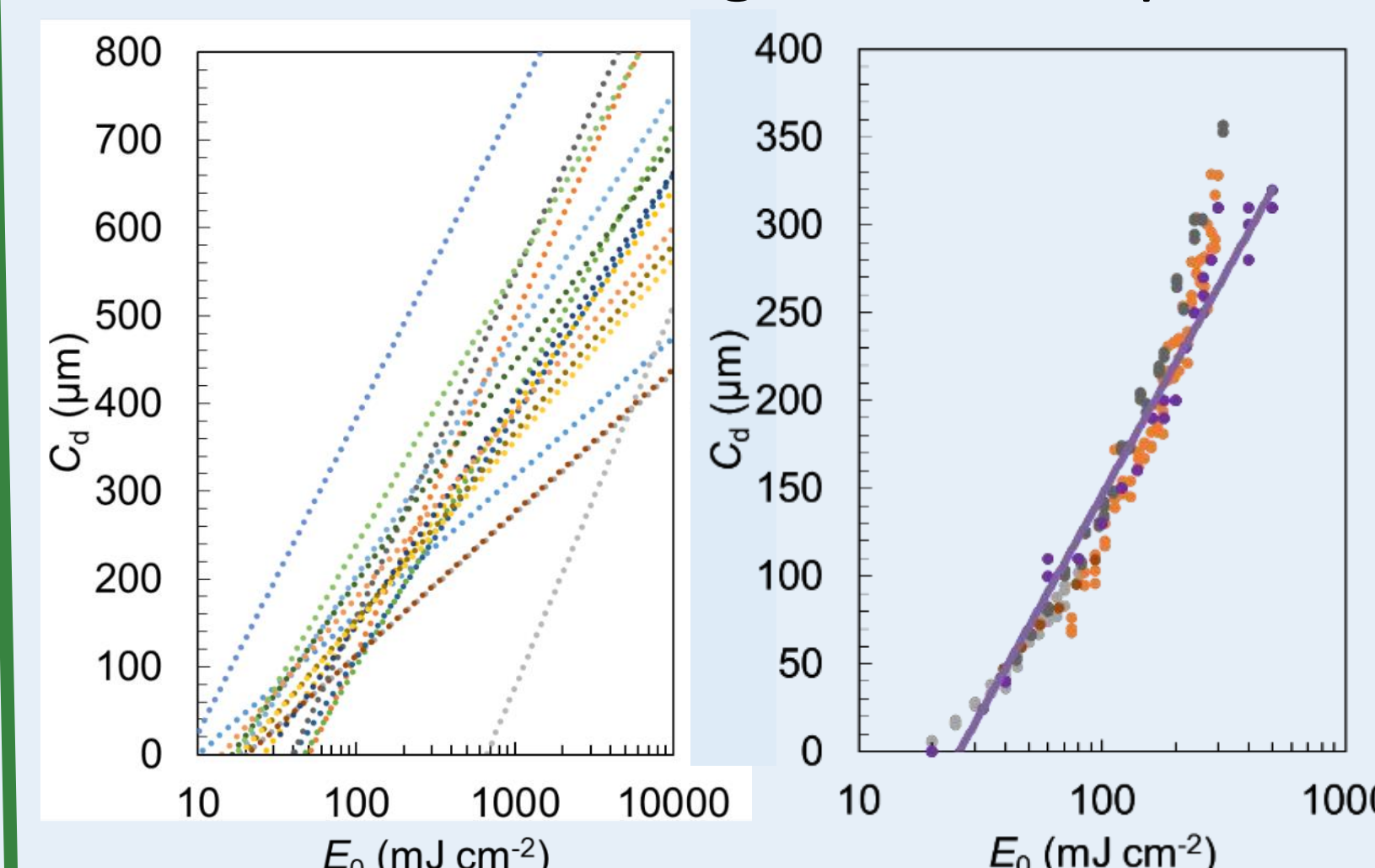
Divergence heterogeneity is also notable

- Most likely origin of the irradiance heterogeneity, pixel level surface topography, cannot be fixed by user

Interlaboratory Study

Phase 1

Academia, industry, and government
Six countries spanning 3 continents
Measure the working curve – no protocol

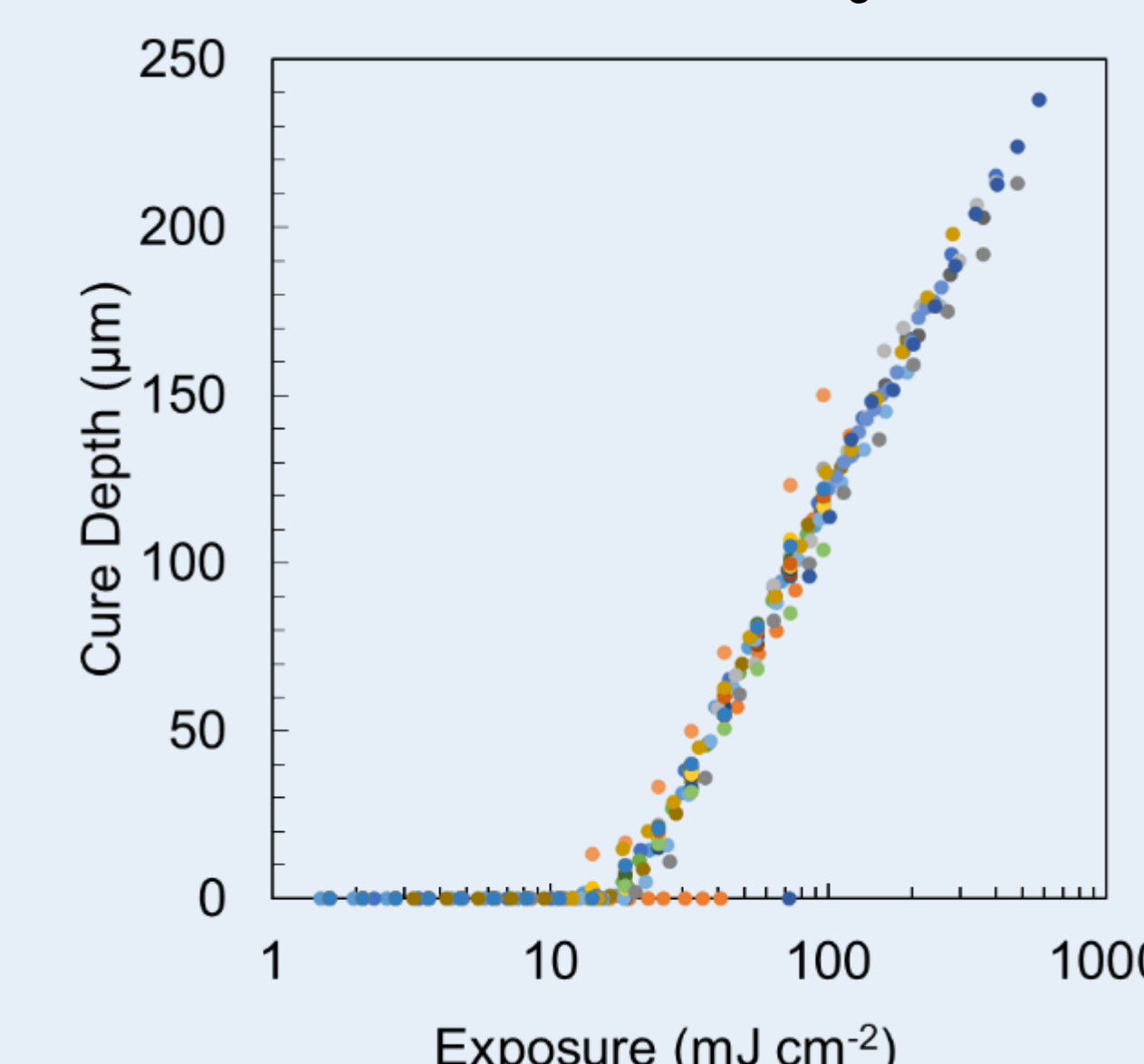
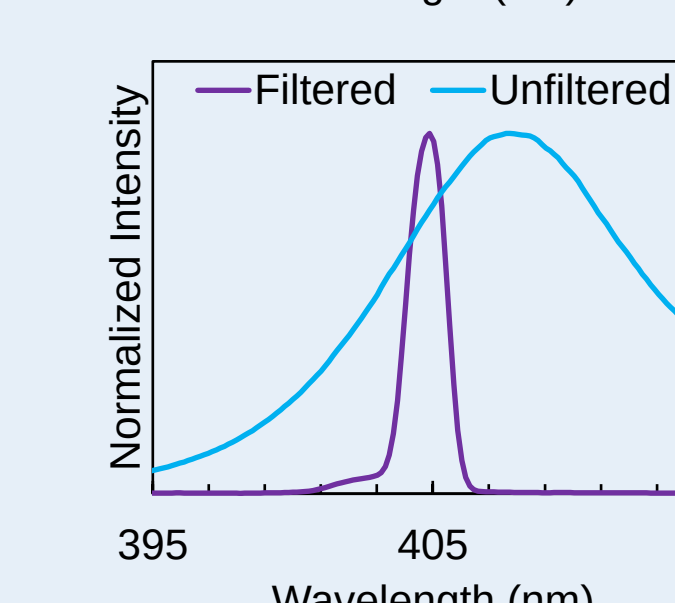
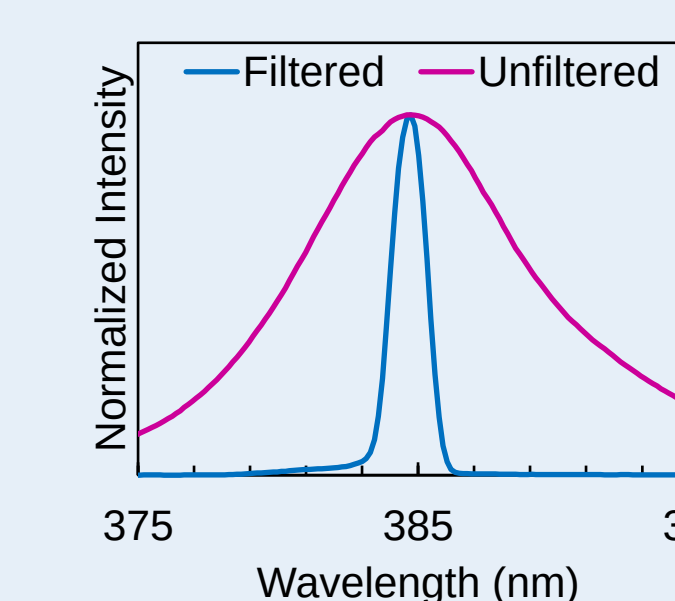
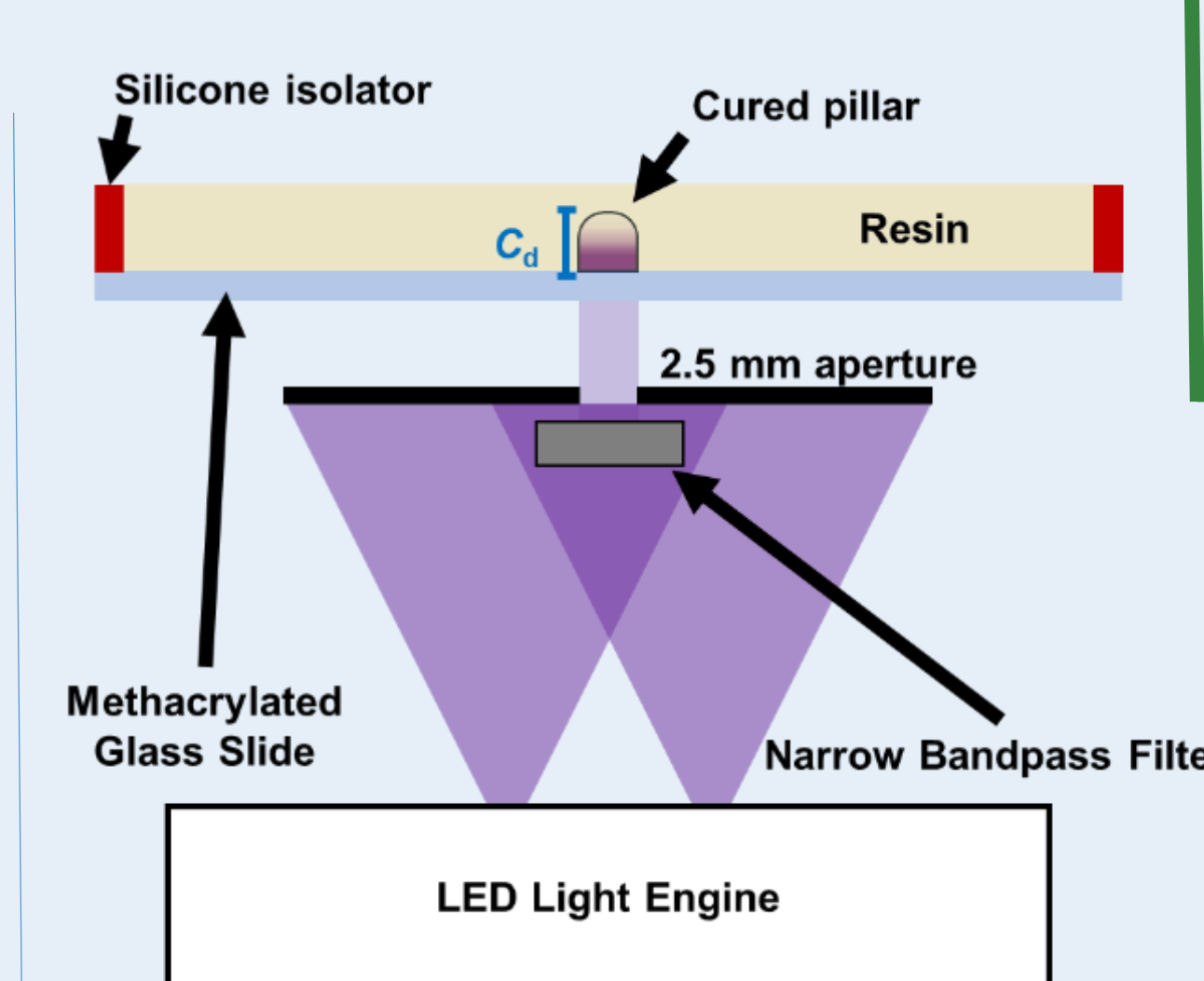


D_p vary by 7x - E_c vary by 70x

Actual data upward sloping curve
Jacobs model doesn't predict this

One dataset follows a straight line
Using a narrow bandwidth laser!

Phase 2



The Working Curve

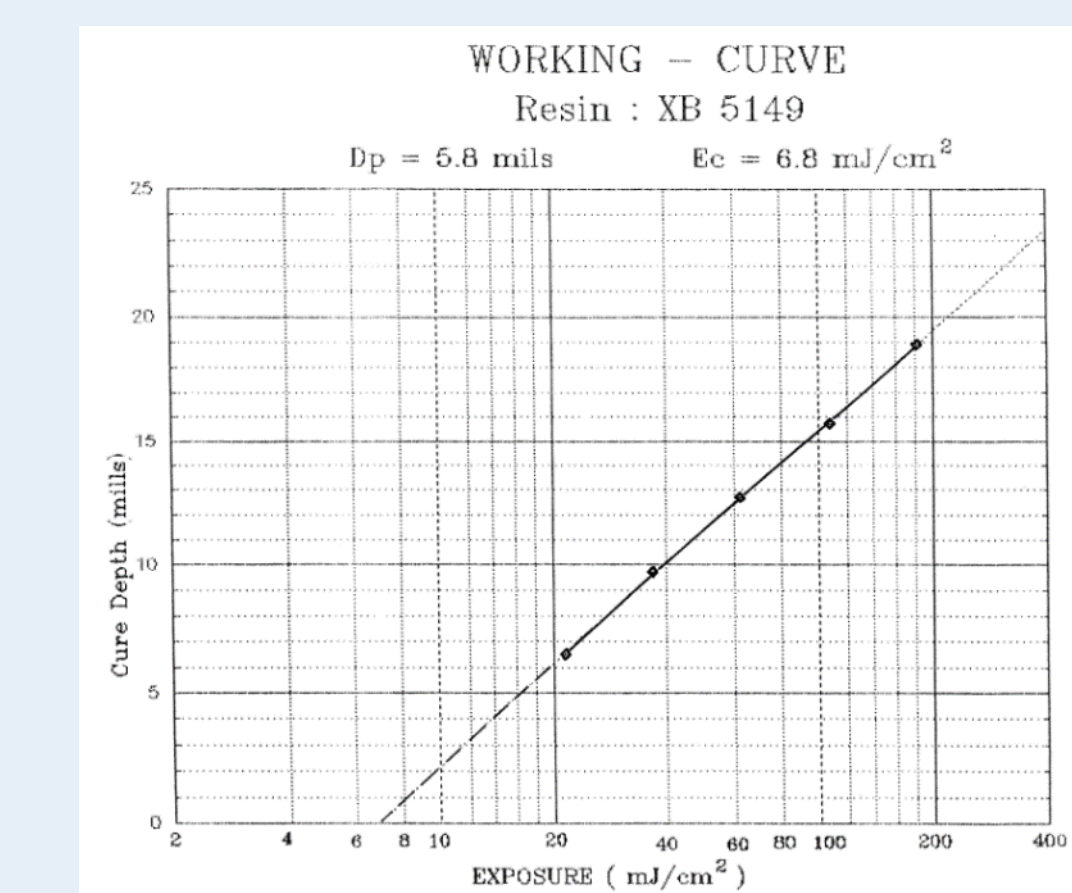
Published in 1992 by Paul Jacobs

Relates cure depth (C_d) and light exposure (E)

$$C_d = D_p \ln\left(\frac{E_0}{E_c}\right)$$

D_p – Depth of light penetration (slope)

E_c – Critical radiant exposure for gelation (x-intercept)



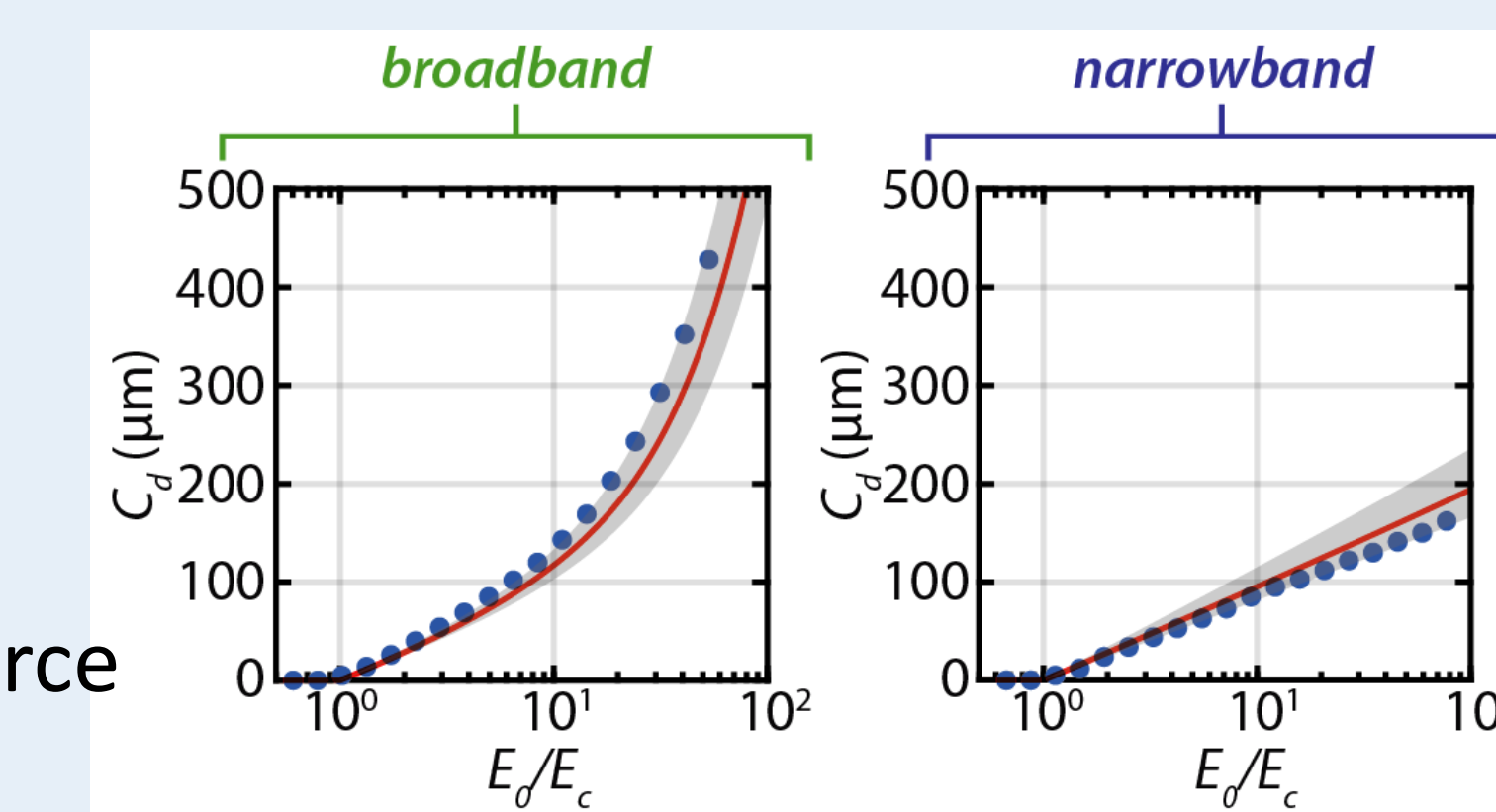
Polychromatic Model

$$\frac{E_0(C_d)}{E_c} = \frac{\int_0^\infty \alpha^{PI}(\lambda) S(\lambda) d\lambda}{\int_0^\infty \alpha^{PI}(\lambda) S(\lambda) \exp(\alpha^{resin}(\lambda) C_d) d\lambda}$$

α^{PI} extinction spectrum of photoinitiator

$S(\lambda)$ function capturing spectrum of light source

α^{resin} extinction spectrum of entire resin



- 385 nm and 405 nm light sources
- Notch filtered ~1.5 nm bandwidth
- 8.8 or 8.0 mW/cm², respectively
- Calibrated by NIST radiometry group
- Logarithmic exposure spacing

16 points, 4 points below E_c

