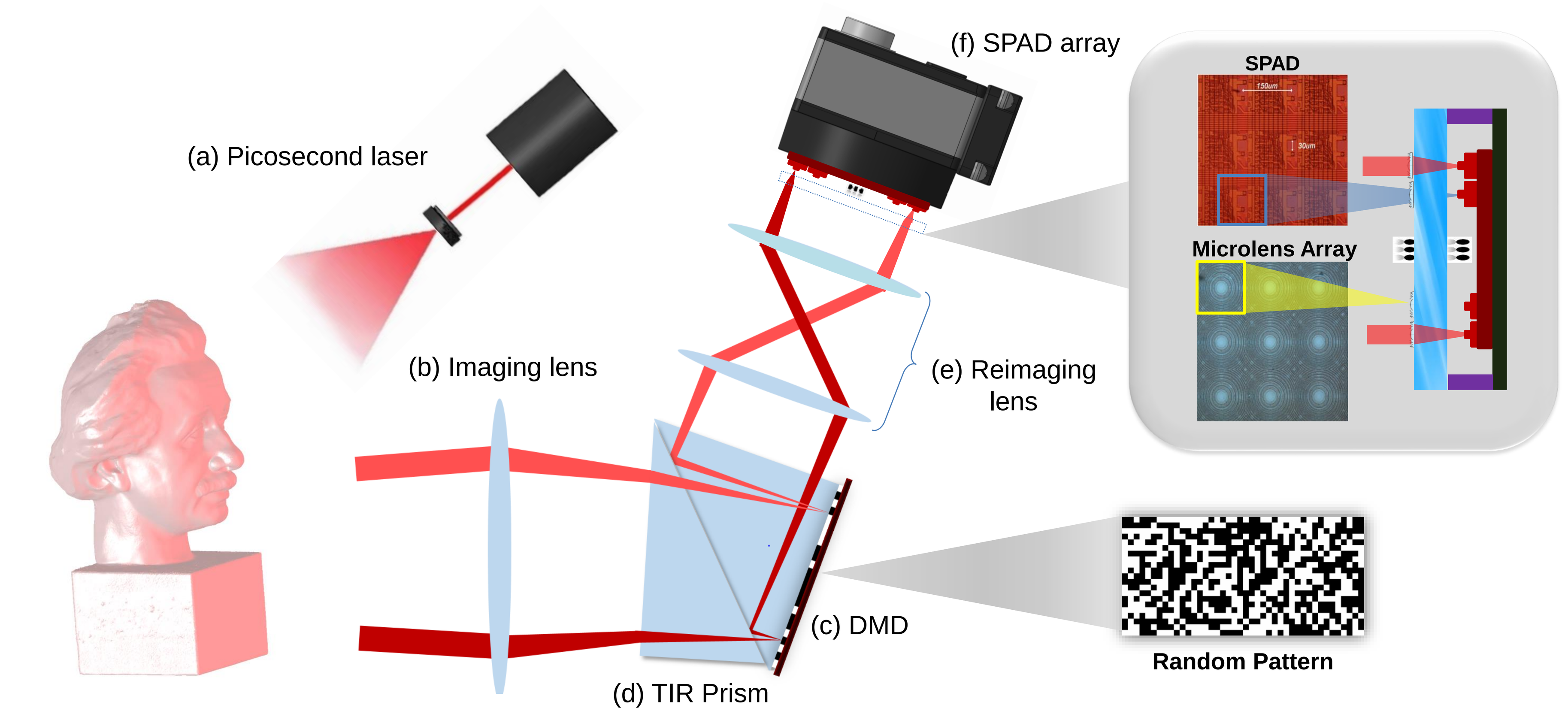
Depth and Transient Imaging with Compressive SPAD Array Cameras

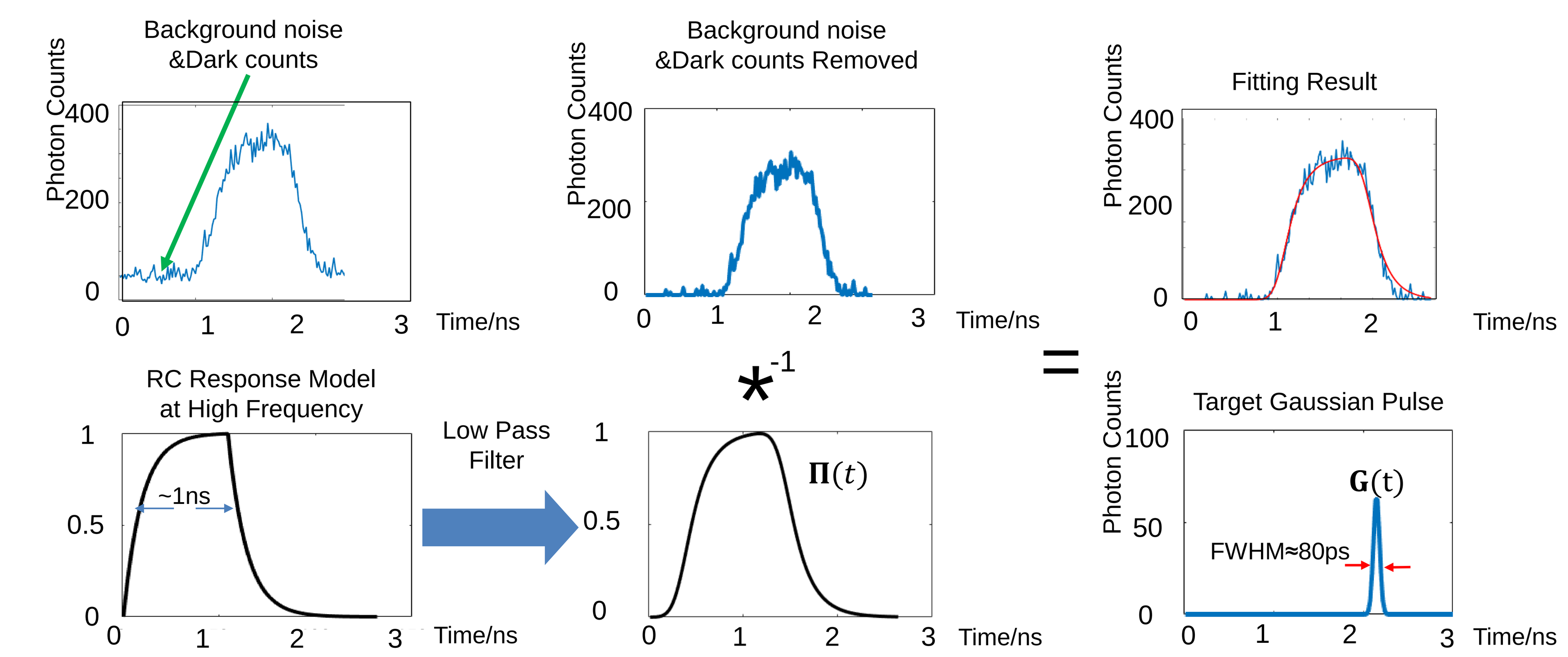
Qilin Sun — KAUST
Xiong Dun — KAUST
Yifan Peng — UBC&KAUST
Wolfgang Heidrich — KAUST

Background and Our Solution

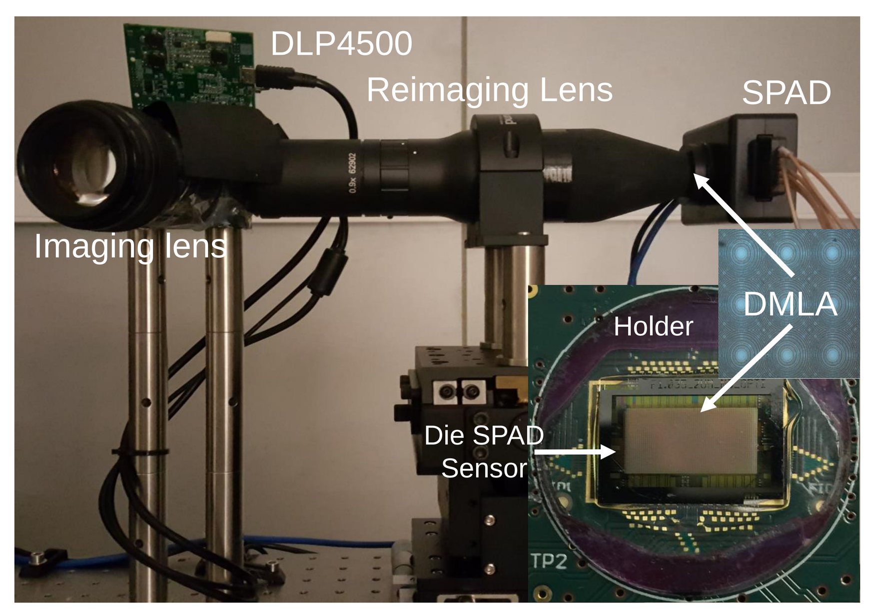
Existing time-of-flight depth imaging and transient imaging systems are limited either in terms of **spatial&temporal** resolution or are prohibitively **bulky&expensive**.

By jointly designing optics, mechanics, electronics, and computation, we overcome the spatial resolution(64×32) limit of Single Photon Avalanche Diode(SPAD) arrays by compressive sensing(image resolution up to 800×400) and realize a temporal resolution of ~20 picoseconds via a physical temporal PSF model.

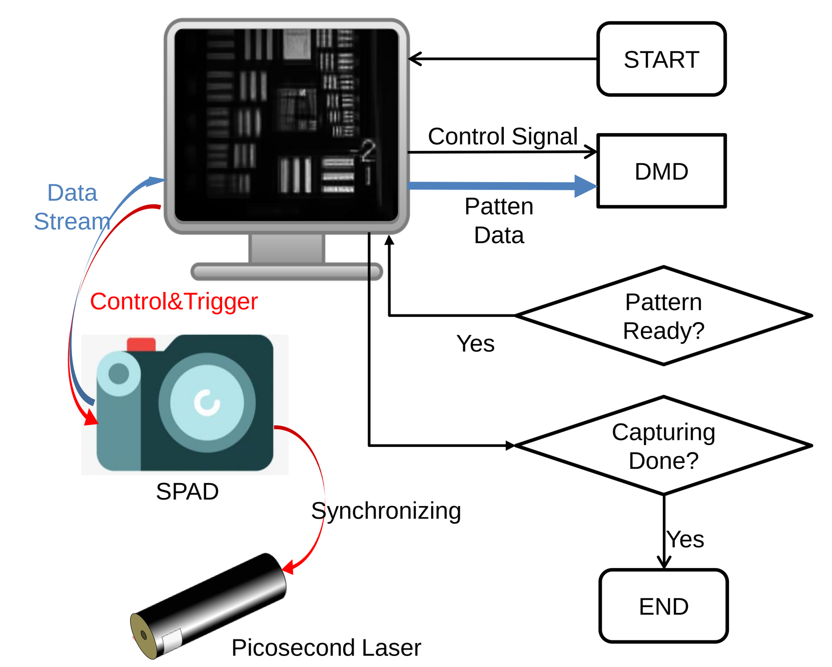




Prototype



Working Flow



Models and Optimization

Our SPAD array is working in TCSPC mode and the measurements from each SPAD pixel could be reconstructed independently with tiling artifacts addressed.

$$\hat{\boldsymbol{X}} = \arg\min_{\boldsymbol{X}} \frac{1}{2}\|\boldsymbol{\Psi}(\boldsymbol{X}) - \boldsymbol{Y}\|_2^2 + \sum_i \boldsymbol{\lambda}_i \boldsymbol{D}_i(\boldsymbol{X})$$

Where $\boldsymbol{Y} \in R^{K\times T\times n\times m}$ is the 4D data sharpened in the temporal domain after modulation, $\boldsymbol{X} \in R^{T\times N\times M}$ is the 3D signal under evaluation, $\boldsymbol{\Psi}$ is an operator that maps the random patterns to individual pixels at each layer, and $\boldsymbol{D}$ is 3D TV regularizer.

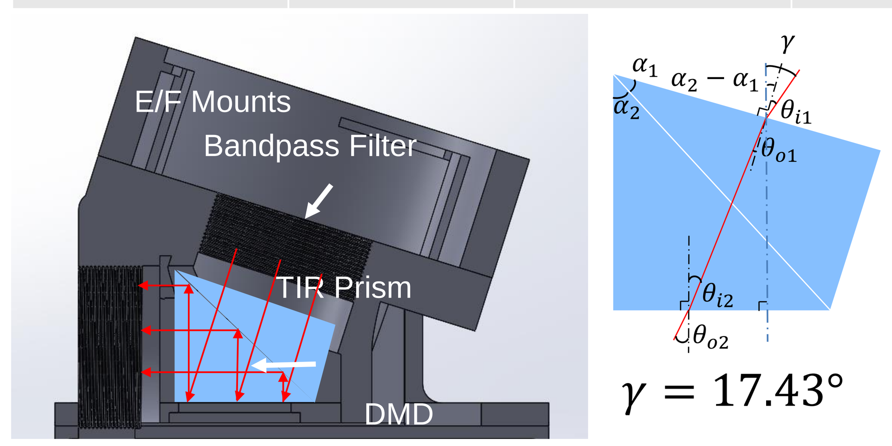
As the picosecond laser pulse is approximately Gaussian and has a FWHM ~80ps, the target Gaussian pulse is shown and denoted as $\boldsymbol{G}$ who has fixed σ. Therefore, we can estimate the depth μ through solving a least square problem.

$$\min_{A,\mu}\left\|\boldsymbol{G}(t;A,\mu) \star \boldsymbol{\Pi}(t) - \hat{\boldsymbol{Y}}\right\|_2^2$$

Where $\hat{\boldsymbol{Y}}$ is the raw sensor data We present the sharpened sensor data $\boldsymbol{Y}_i$ for each pixel i as a sequence of Gaussians $\boldsymbol{G}$.

Optical Parameters in Experiment

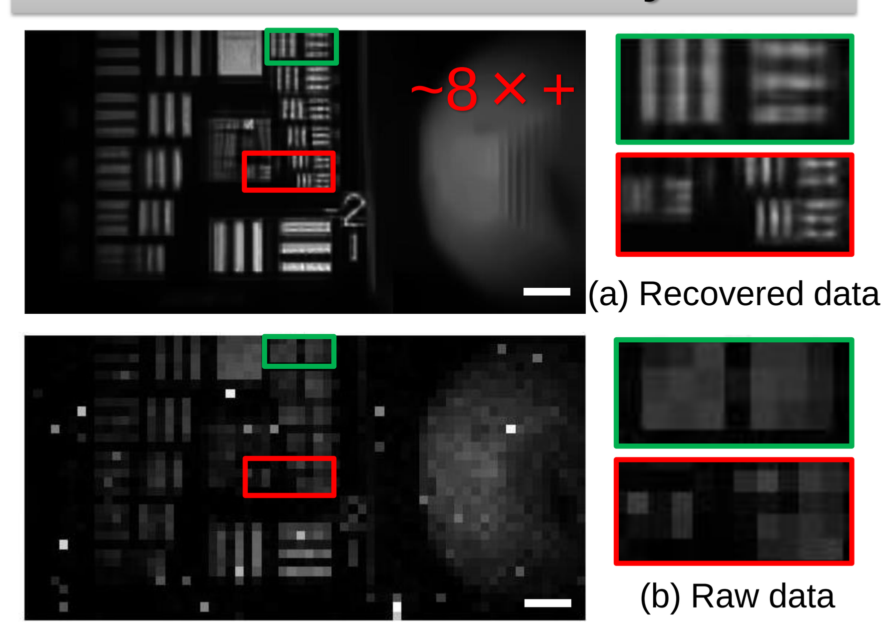
Laser		DMLA		Auxiliary Optics	
WaveLength	655nm	Focal Length	1.035mm	Imaging	Canon 85mm Lens
Average Power	~1mW	Structure	2π period 2^4 Phase Level	Reimaging	Inverted 0.9X Edmund Double Side Telecentric
FWHM	~80ps	Effiency($f/20$)	52.87%	DMD	TI DLP4500
Repetition Rate	50MHz	Fabrication	Lithography(0.7μm) +RIE etching	DMD optical system	Shown Below



SPAD Array Settings

Integration Time	Harware Binning	Gate Width	Shift per Cycle	Photons Received
52μs	1280	830ps	20ps	~40-60/pixel

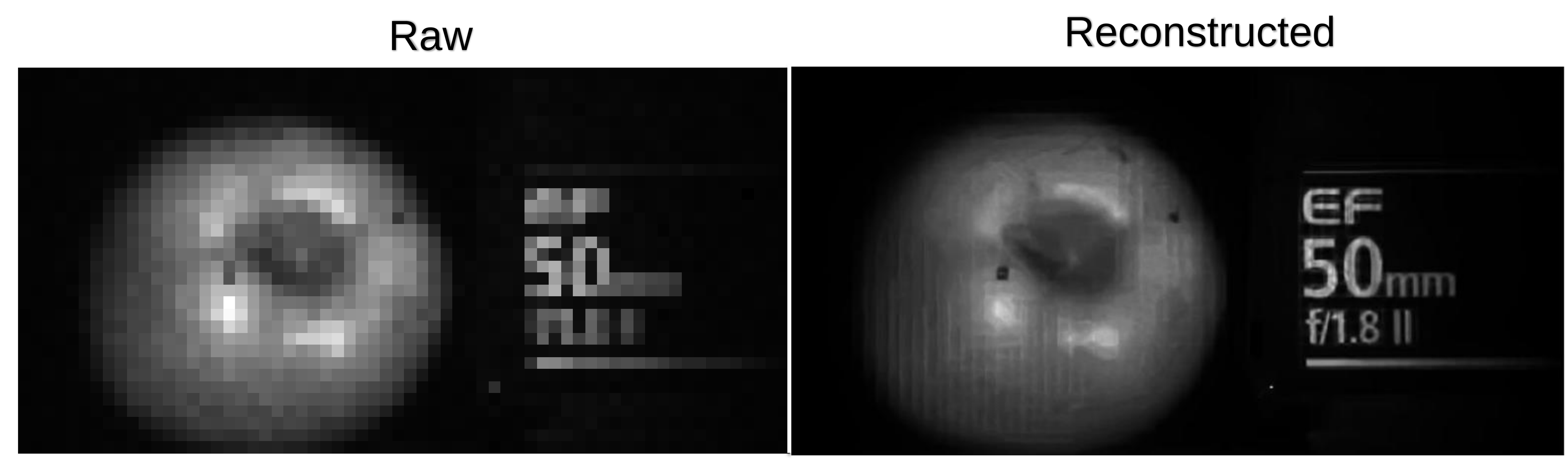
Resolution Analysis



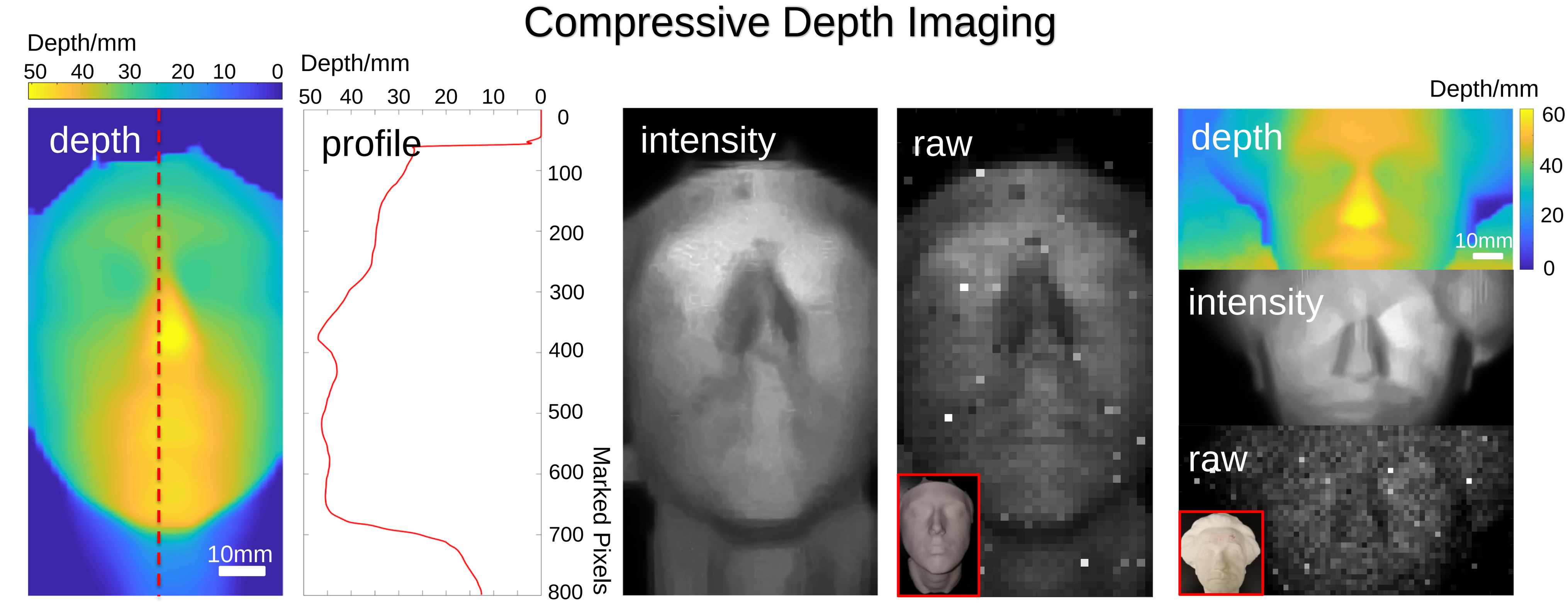
(a) Recovered data

(b) Raw data

Results



Compressive Depth Imaging



Light Concentrated by a lens / Transient Scene