

Micrite

Towards a Sub-100-Micron Distributed
Sensor System

Christopher Thomas

Outline

➤ **Overview**

- Optics
- Deblurring
- Analog to Digital Converter
- Concluding Remarks

Contributions

- System requirements for 100 micron surveillance mote
- Subsystem implementations:
 - Image sensor with on-die optics
 - Deblurring algorithm for on-die optics
 - Log-ramp ADC (ultra-low energy)

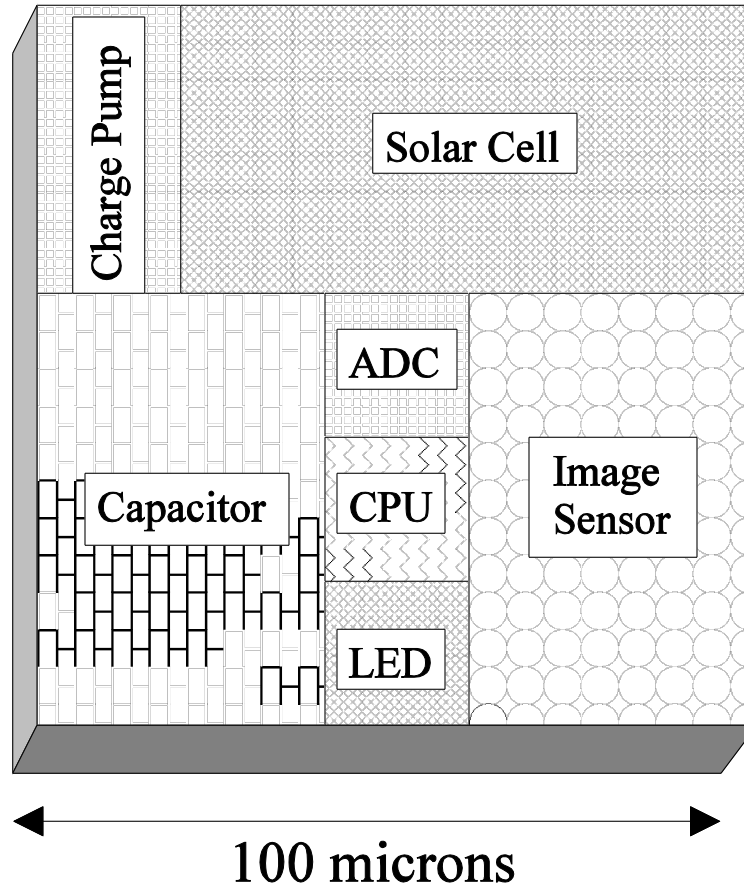
Design Goals

- Very small (100 micron) sensor mote fabricated using CMOS-compatible technologies
 - Inexpensive and proven technology.
 - Very large number of devices per wafer.
- Capable of acquiring images for surveillance
 - B/W or colour image acquisition.
 - Digitized with enough fidelity for feature extraction and object tracking.
 - Capable of operating on ambient light power budget.

Design Specifications

| | | |
|----------------------------|--|-------------------------------------|
| Subsystem Area | 2000-3000 μm^2 (large) | 500-1000 μm^2 (small) |
| Power Budget | 30 nW (outdoor) | 0.15 nW (indoor) |
| Charge Storage | 1 pF, 0.4 V swing, 0.4 pC charge | |
| Recharge Time | 13-40 μs (25-77 kHz) (outdoor) | 3-8 ms (125-330 Hz) (indoor) |
| Image Dynamic Range | ≥ 6 bits (raw images) | ≥ 10 bits (for deblurring) |
| Image Pixels | ≥ 100 | |

Sample Floorplan



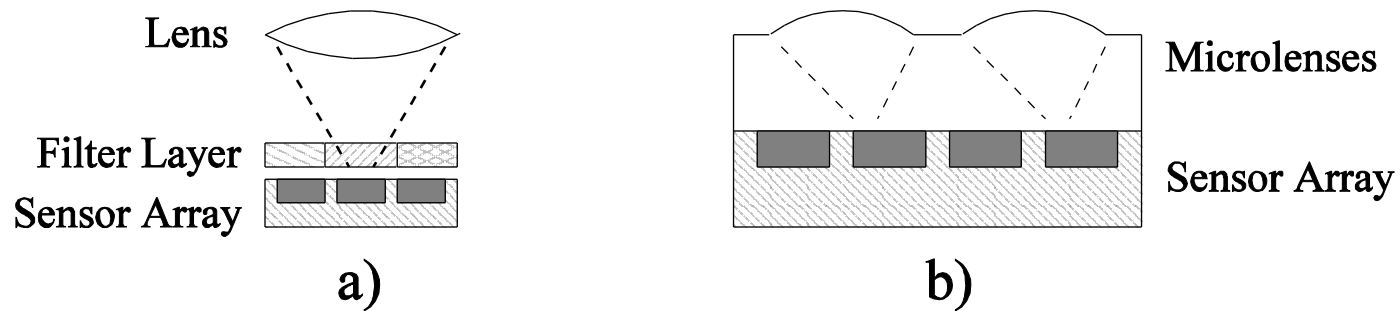
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- Overview

➤ **Optics**

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- Concluding Remarks

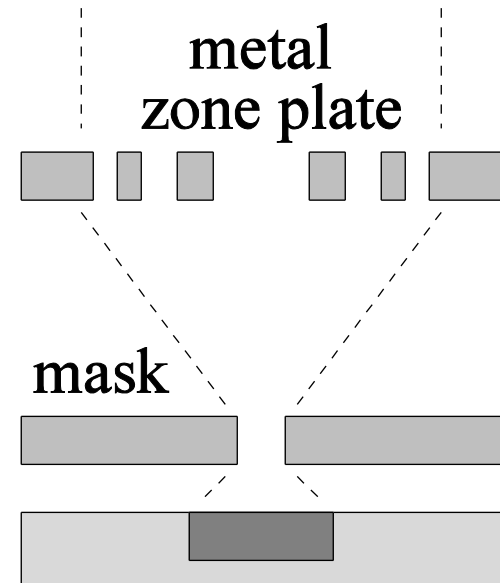
On-Die Optics



- Images formed by lenses on die, rather than separate component
- Existing project: TOMBO

On-Die Optics

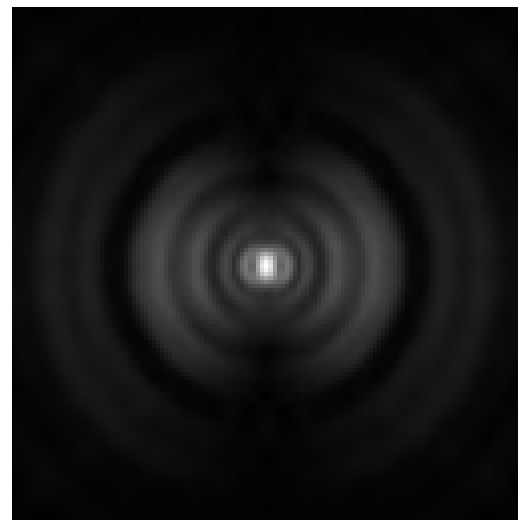
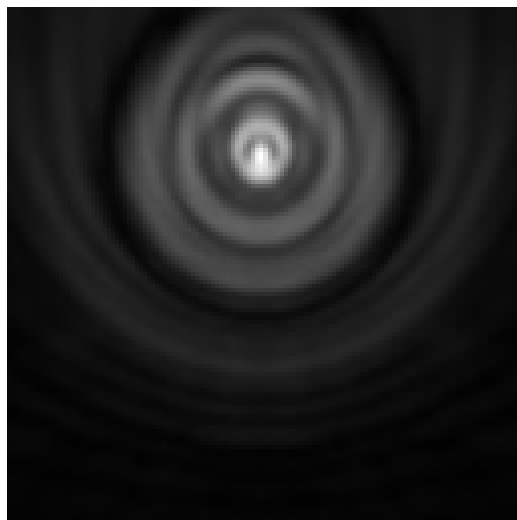
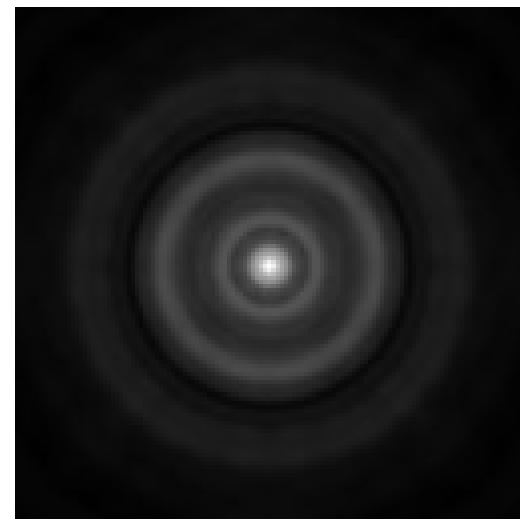
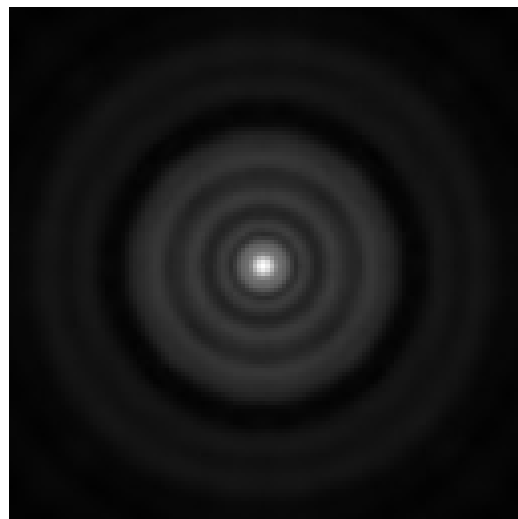
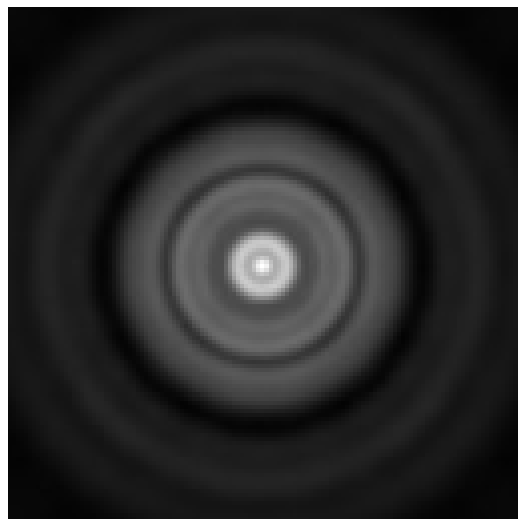
- Metal zone plate optics
- Made using existing process layers
 - No extra steps, no extra cost.
- Side effects:
 - PSF varies with wavelength
 - PSF varies with polarization



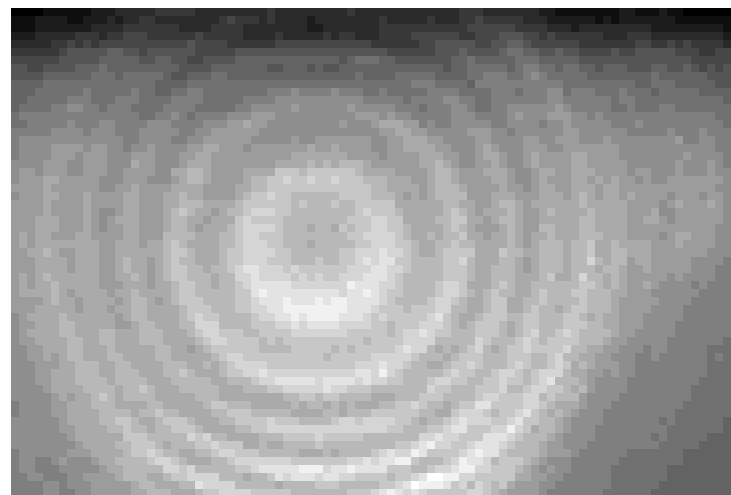
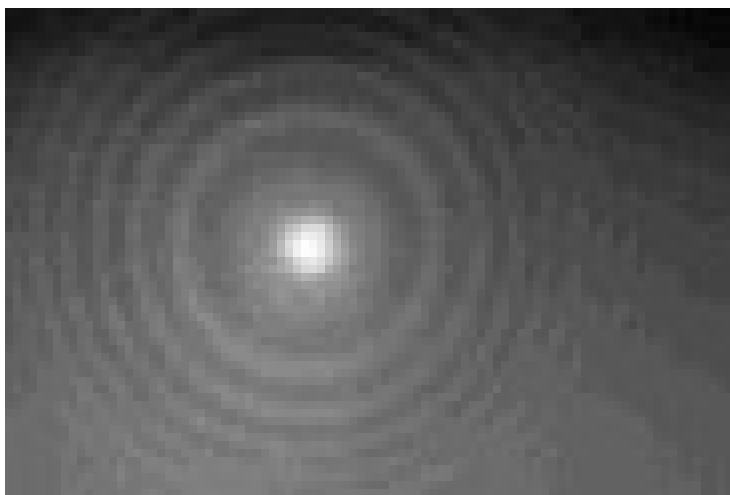
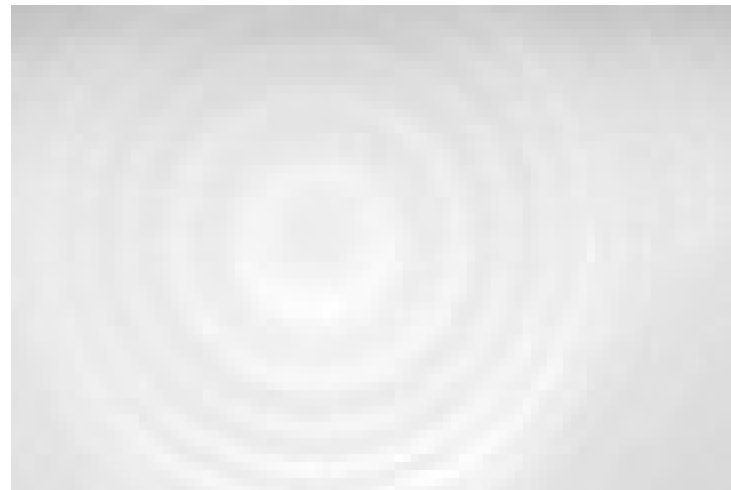
Optics Simulations

- Point spread function is a focused spot surrounded by fringes.
- Fringe geometry and brightness varies with wavelength for a given zone plate.
- Off-axis light displaces the spot per thin lens, and changes fringe geometry.
- Polarization effects give an elliptical spot.

Optics Simulations

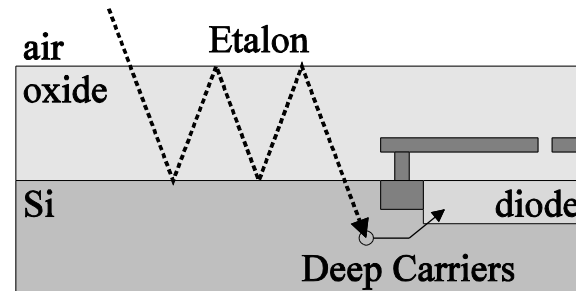
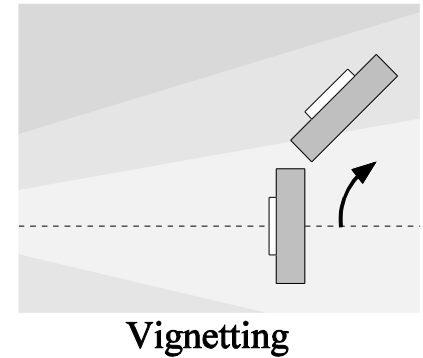
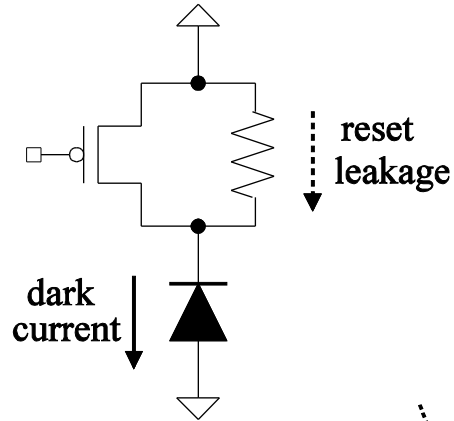


PSF Measurements

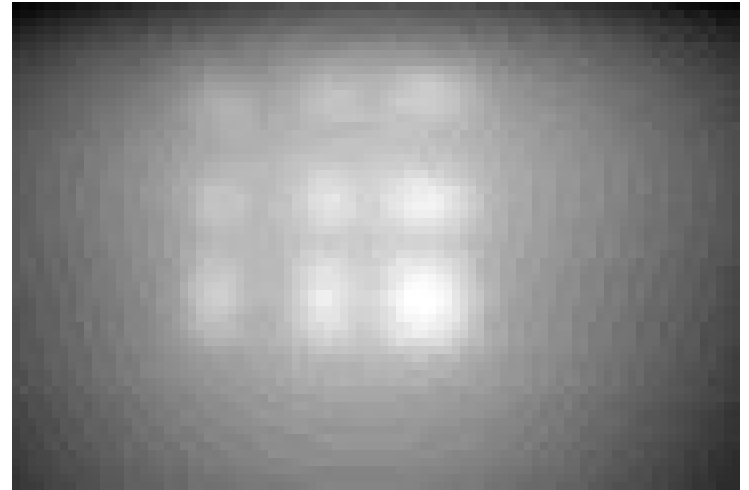
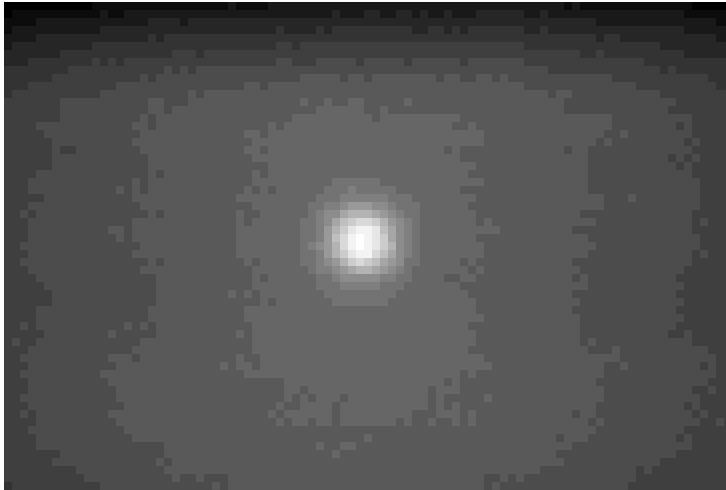


PSF Measurements

- Artifacts:
 - Etalon
 - Deep carriers
 - Leakage
 - Vignetting
 - Narrow gap reflection



PSF Measurements: LED Tests



- No etalon fringes (short coherence length)
- Spot size (FWHM) **0.15-0.20 radian**

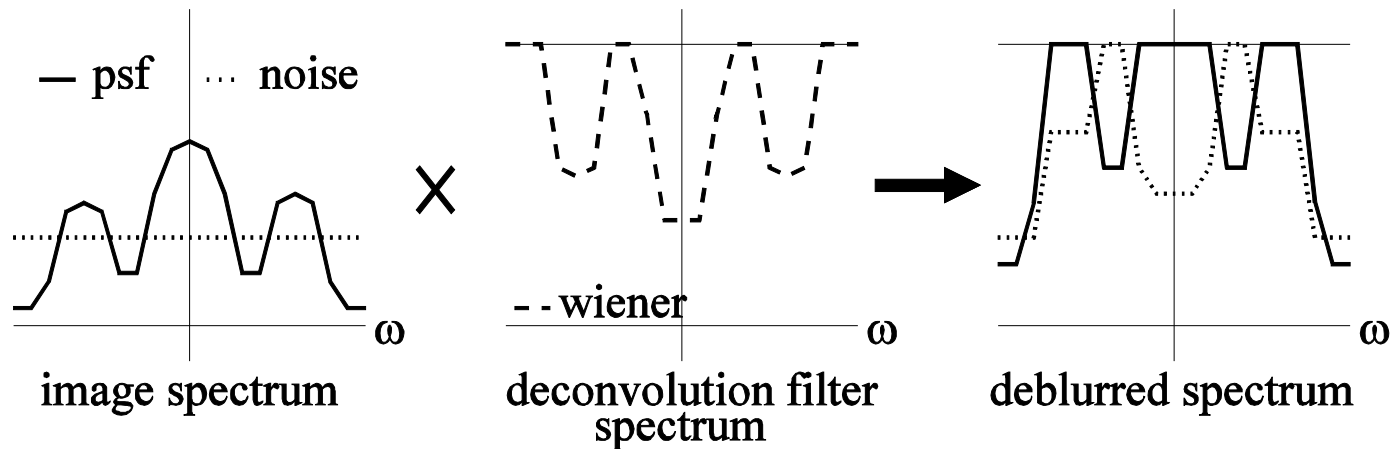
Outline

- Overview
- Optics

➤ **Deblurring**

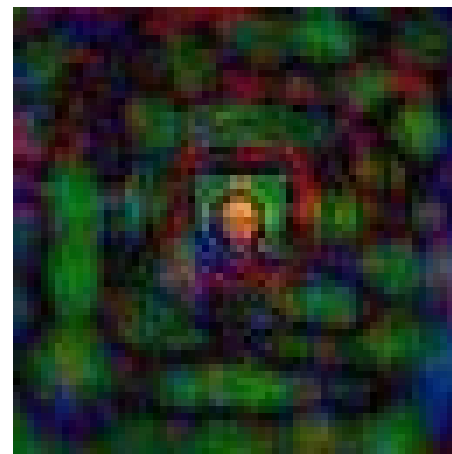
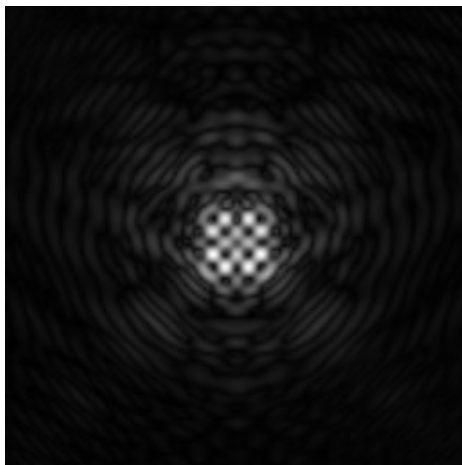
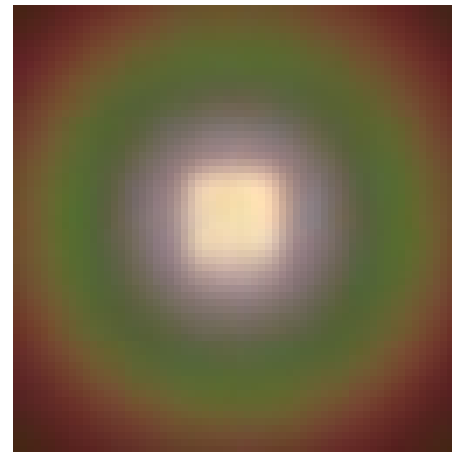
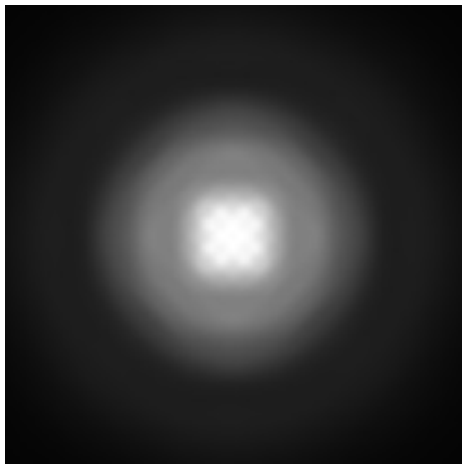
- Analog to Digital Converter
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Deblurring: Method



- Model blurring as noisy convolution.
- Use Wiener deconvolution filter.
- Boosts attenuated spectral components, with boost clamped by expected noise floor.

Deblurring: Simulations



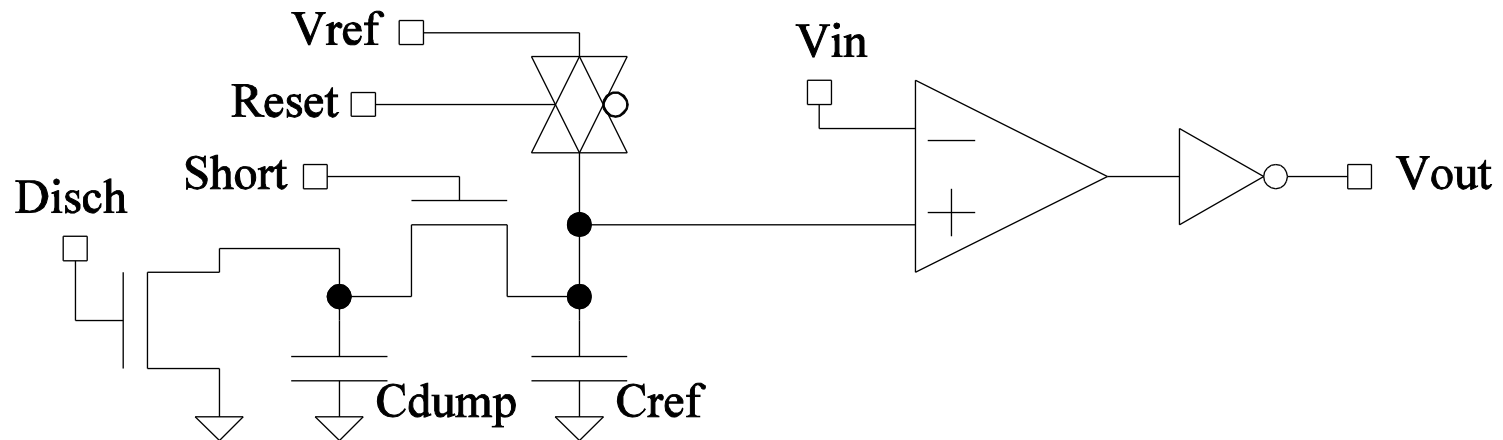
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- Deblurring
- **Analog to Digital Converter**
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ADC Design

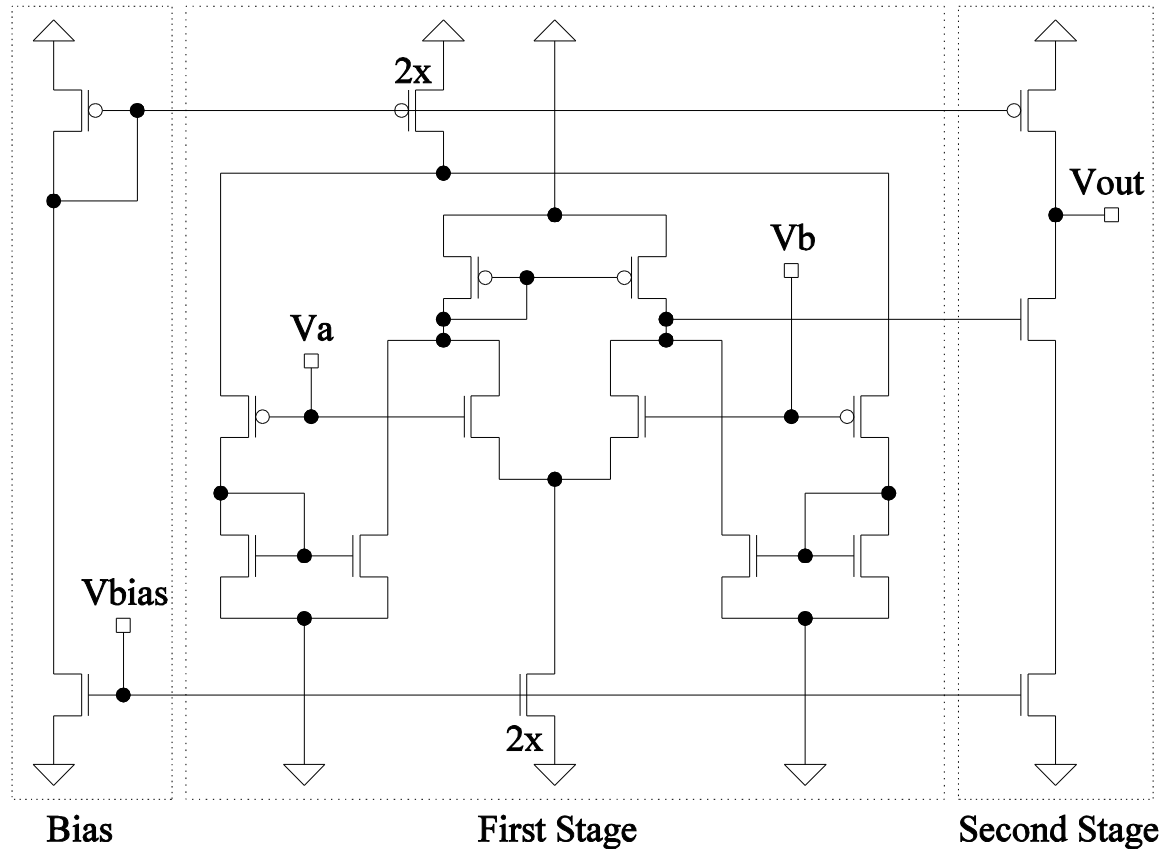
- Using a log-ramp architecture.
- Log scale captures the full image dynamic range with the fewest number of quantization levels.
 - Not the fewest number of comparisons!
- Ramp converter is the time-domain equivalent of flash conversion (one comparison per quantization level).

ADC Design



- Reference voltage is sampled, and capacitively divided to produce a geometric sequence of levels.
- Pixel voltage is assumed to be stable during conversion.

ADC Design



- OTA with N and P differential pairs for rail to rail input.

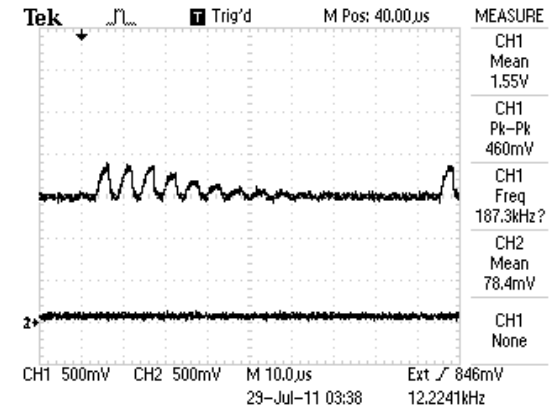
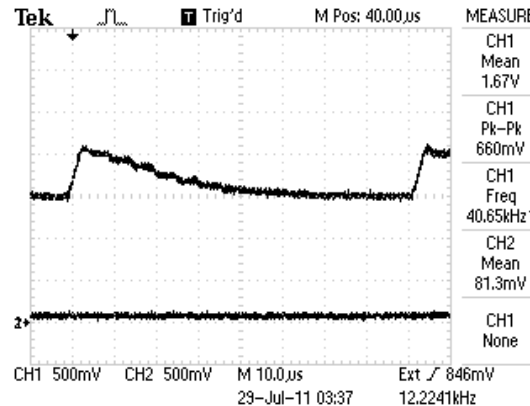
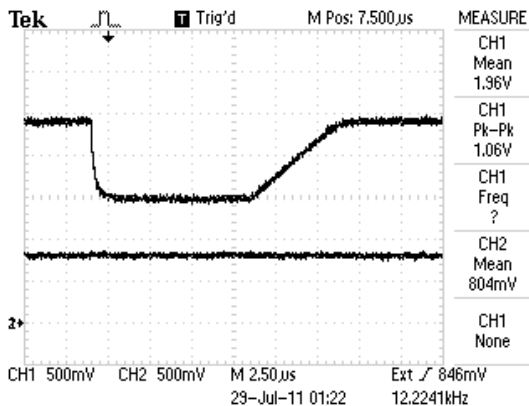
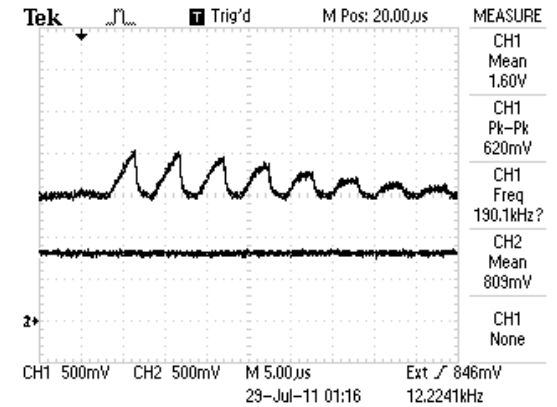
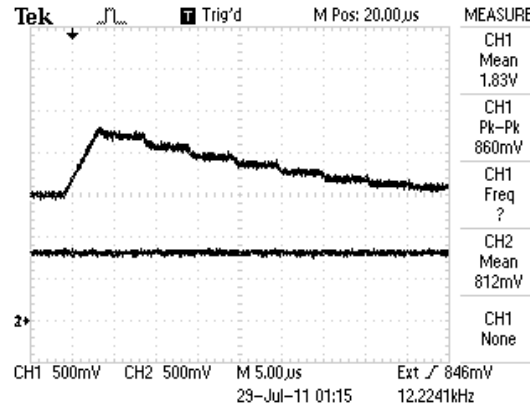
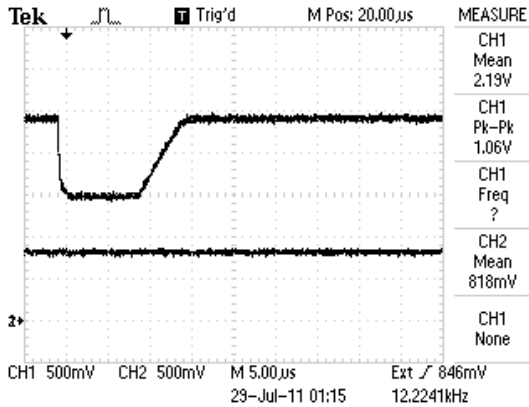
ADC Simulated Performance

- 0.8 V to 1.2 V supply
- Ramp step noise ~ 10 mV
- Expect **5-6 bits** equivalent dynamic range

- Bias current 6-8 μA gated, 10-20 μA not
- Minimum step duration 50 ns
- **1.7-4.7 pC** per digitization

- Configurations: 3:1, 2:1, 1:1 dividers

ADC Measurements

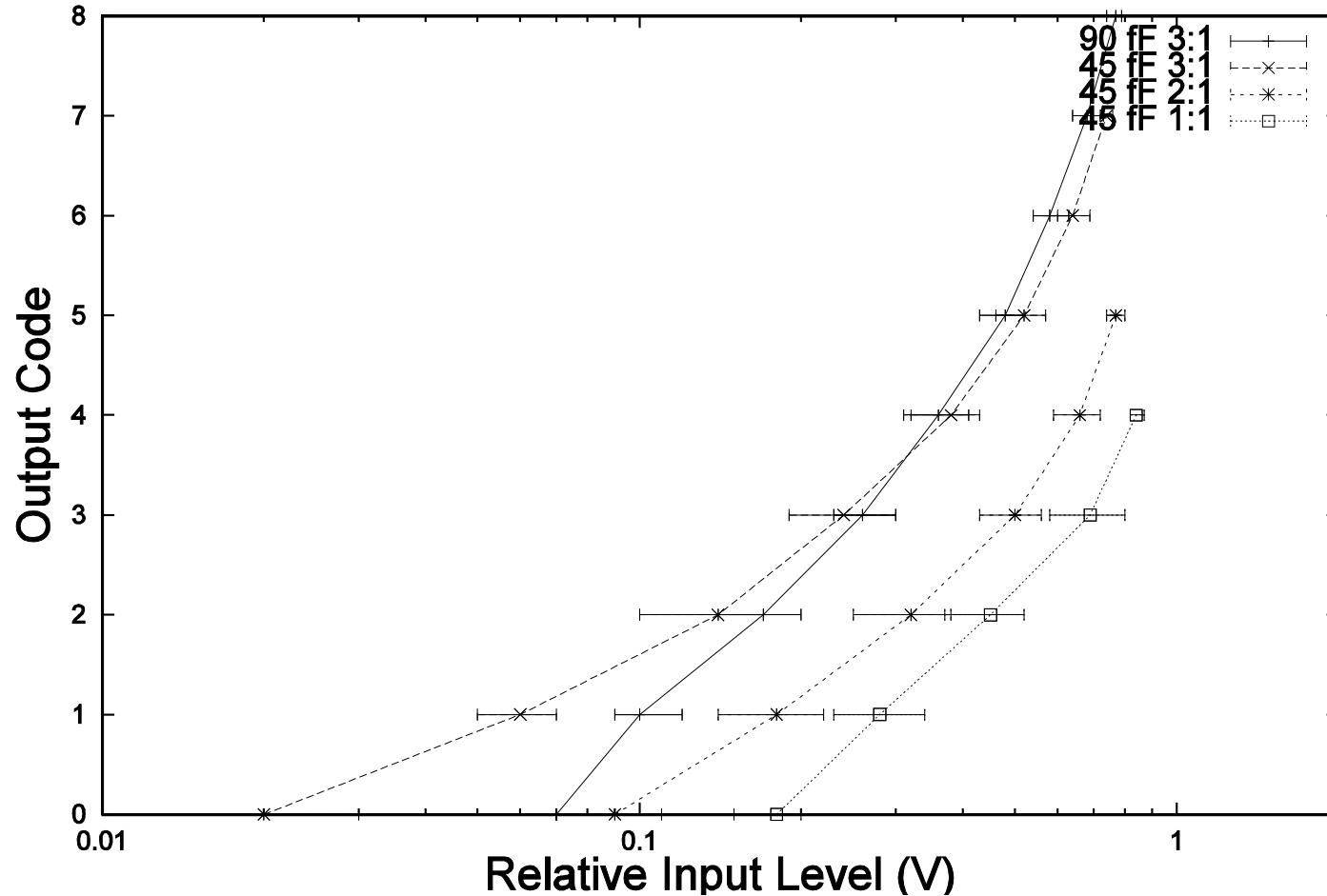


ADC Measurements

- Operates as-designed at 0.8 V and 1.2 V
- Bias current 6 μA per ADC
- For large reference voltages, first few steps of the ramp are not geometric due to NFET pass transistor
- Experiment output buffer is very slow; DC tests only.

ADC Transfer Functions: 0.8 V

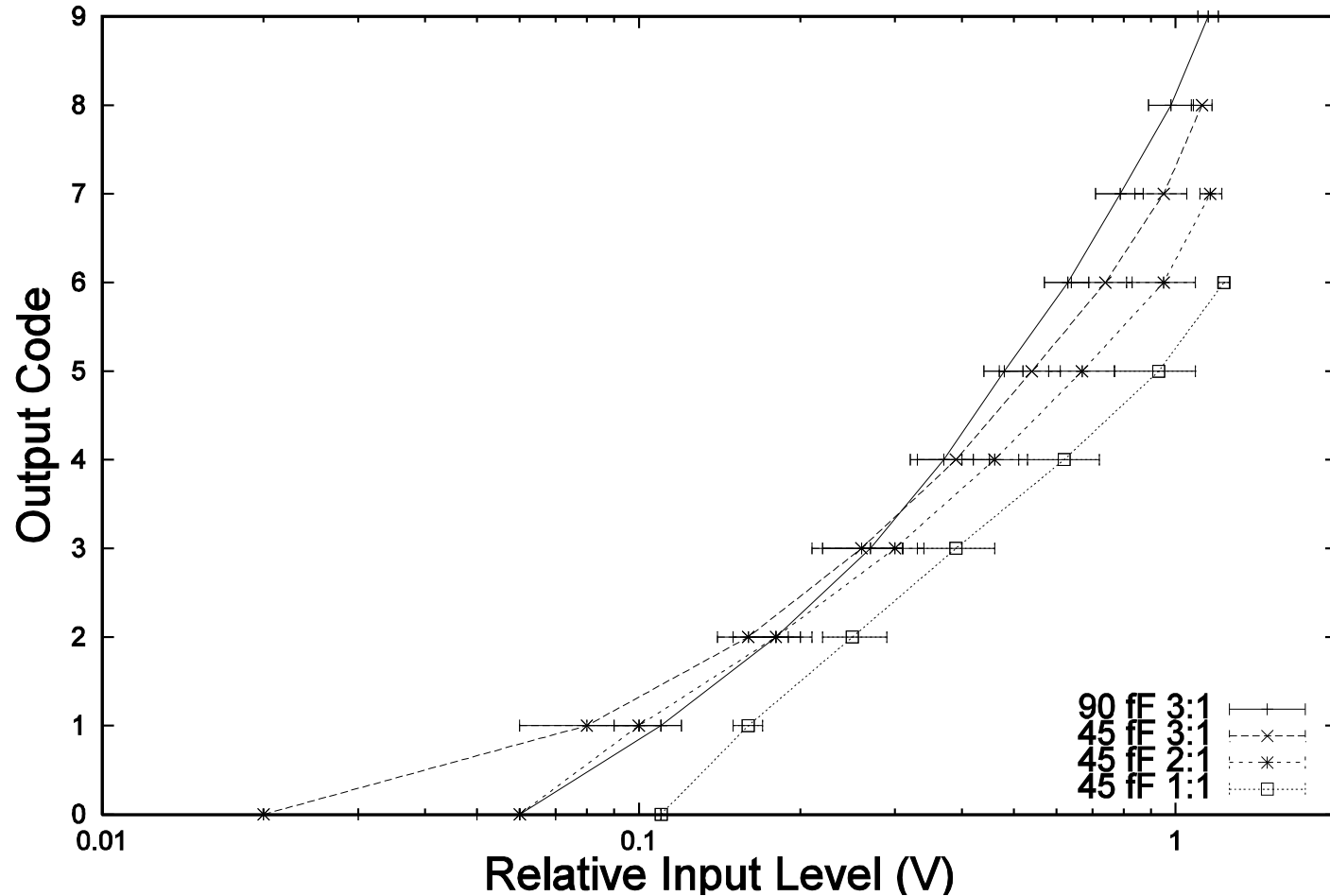
ADC Transfer Functions (All)



- 3-4+ bits equivalent dynamic range 25

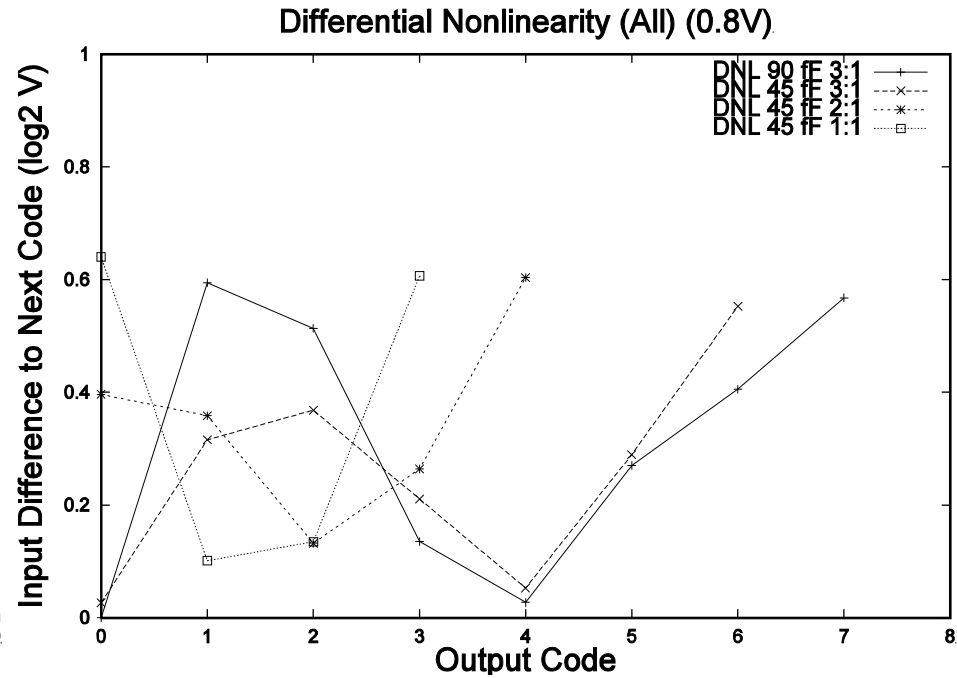
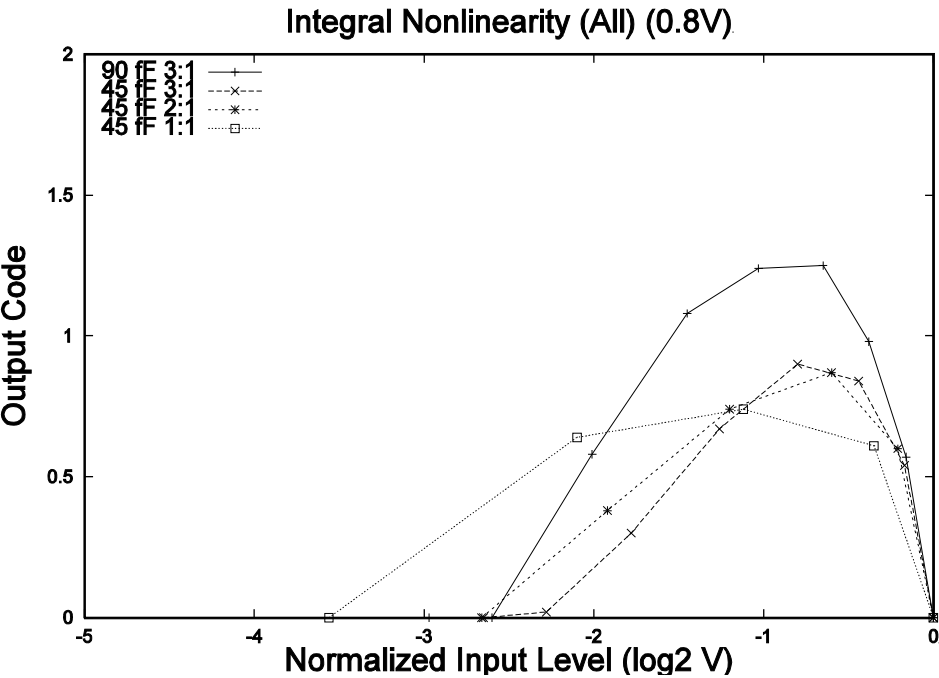
ADC Transfer Functions: 1.2 V

ADC Transfer Functions (All)



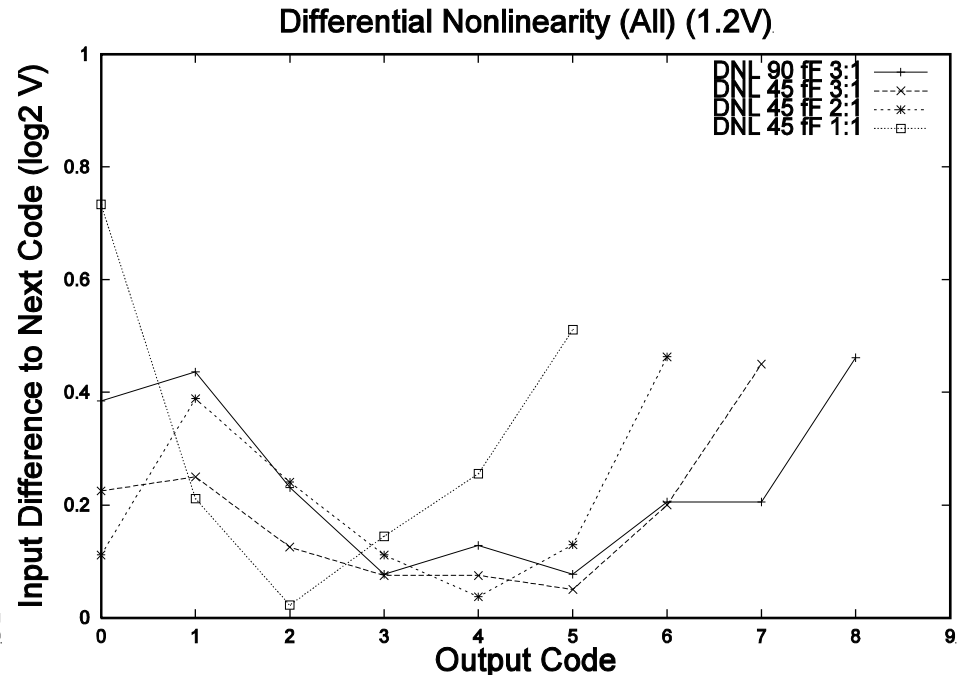
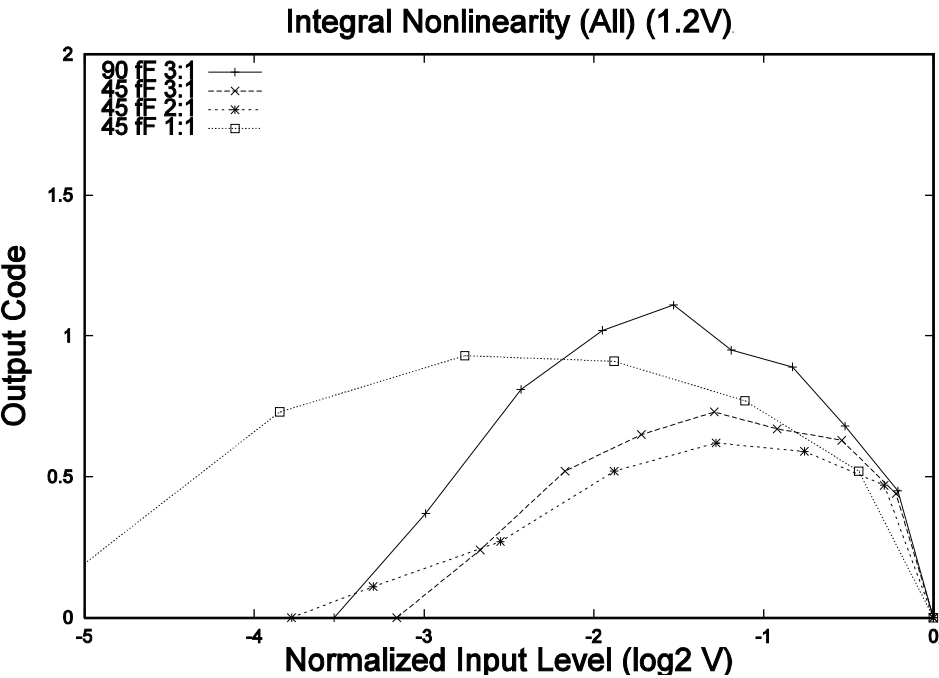
- 3-4+ bits equivalent dynamic range 26

ADC INL and DNL: 0.8 V



- INL ≤ 1.3 (typ. < 1)
- DNL ≤ 0.6

ADC INL and DNL: 1.2 V



- INL ≤ 1.2 (typ. < 1)
- DNL ≤ 0.5

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➤ **Concluding Remarks**

Conclusions and Looking Forward

- Outlined a design specification for a 100 micron sensor mote.
- Built and demonstrated a fully-integrated image sensor with on-die metal optics.
- Demonstrated a deblurring and colour separation algorithm based on Wiener filtering.

Conclusions and Looking Forward

- Built and demonstrated an ultra-low-energy log-scale analog to digital converter.
- Future work:
 - Optical transceiver
 - Communications and networking protocols
 - On-mote image processing