Image Super-resolution for Ultrafast Optical Time-stretch Imaging

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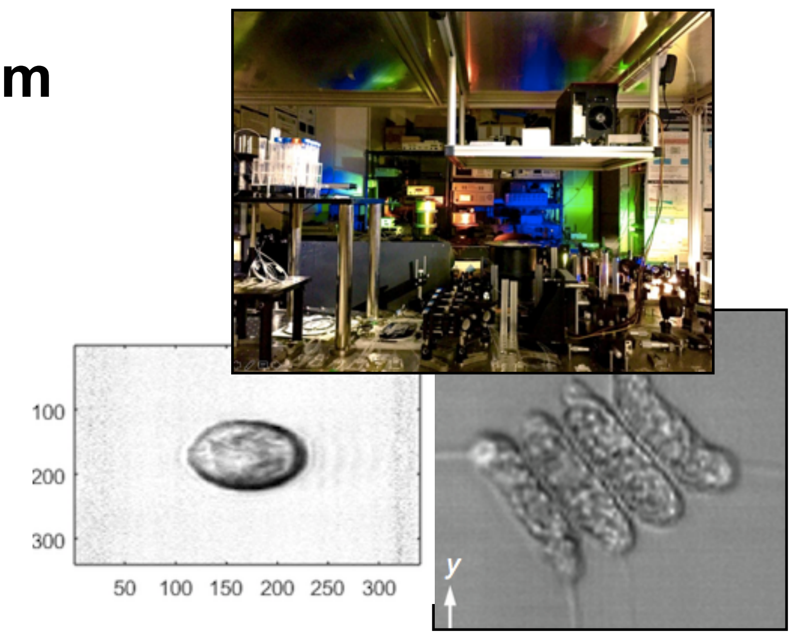
Presentation Outline

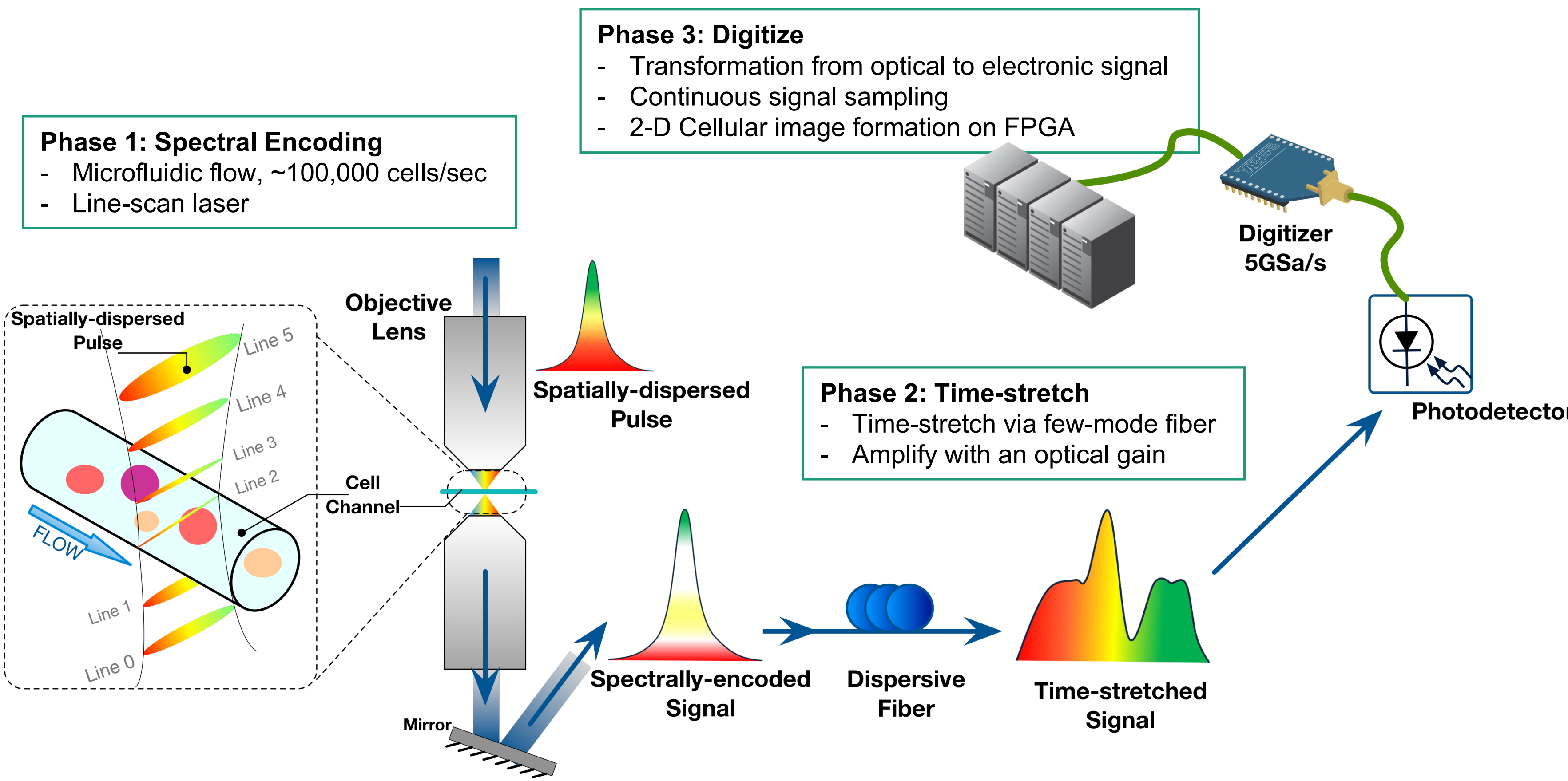
- Introduction of Time-stretch Imaging
- Modeling the Image Sampling
- Super-resolution with Subpixel Shift
- Evaluation Simulation
- Experiment Results
- Summary & Future Work

Time-stretch Imaging

- **Application**
  - **Ultrafast optical microscopy**
    - High-throughput microfluidic (8 m/s)
    - 100,000 cells/s
    - >10 MHz line scanning rate
    - Real-time imaging
  - **Connected with digital system**
    - Cancer cell detection
    - Precision Medicine
- **Challenges**
  - **Expensive oscilloscope**
    - HKD 1,000,000
  - **Huge data processing**
    - 80 GB/ sec
- **Next:** Home-built system

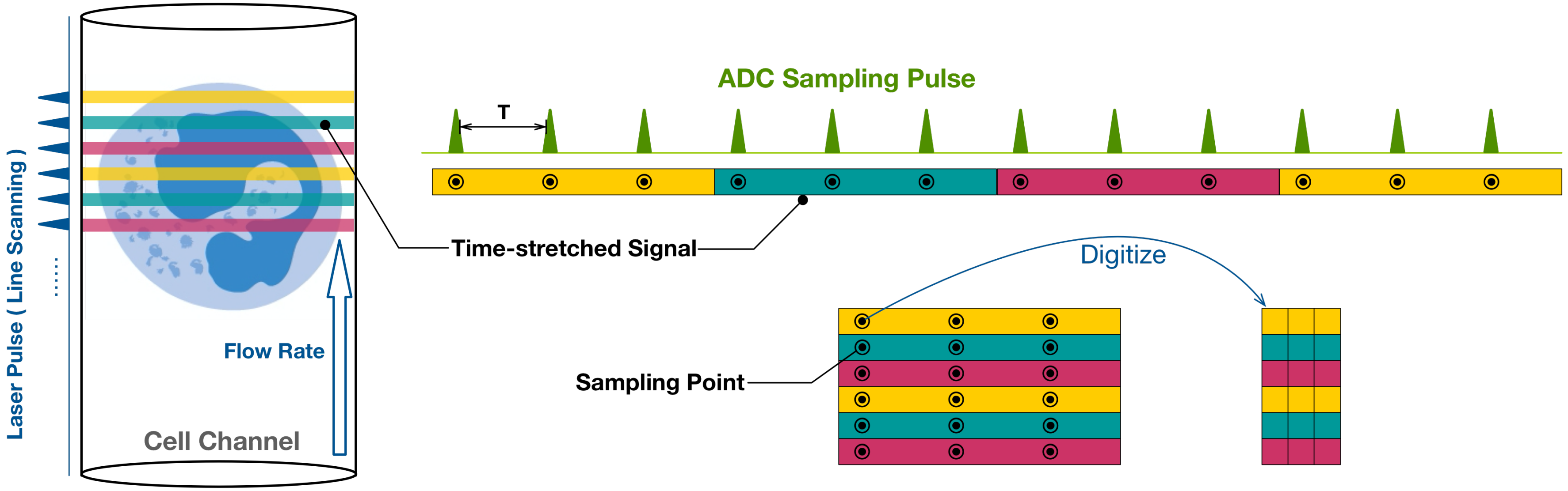


Time-stretch Imaging System



Modeling of Image Sampling

- **Line Scanning and Time Stretch (Optical System)**
  - Fixed frequency line scanning (colorful bands on the cell image)
  - Time-stretch the spatially-encoded signal, generate the continuous signal
- **Normal Line-aligned Sampling (High-speed ADC)**
  - Uniformly sampling the time-stretched signal (3 sampling points per line in following example)
  - Digitize the samples from analog signal to 8-bits grey-scale pixel data
- **2D Image Stack (FPGA, Field Programmable Gate Array)**
  - Construct the cell image



Sampling Model Parameters

- Parameters set in line-aligned sampling

Parameters	Denotation	Sample Value
Laser Pulse Frequency (fixed)	f_{laser}	11.4 MHz
ADC Sampling Frequency	$f_{sampling}$	3.99 GHz
Flow Rate	v_{flow}	1 m/s
Imaging Width	$Width$	250 µm

The slower, the more information be caught In vertical

Spatial imaging range in horizontal

350x
Sampling 350 points per line

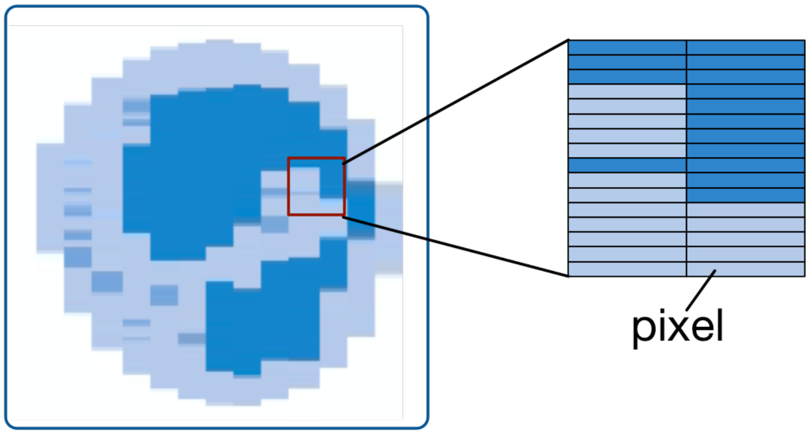
- Calculation of digitized image resolution (unit: pixel/µm)

$$R_{horizontal} = \frac{f_{sampling}}{Width \times f_{laser}} \qquad R_{vertical} = \frac{f_{laser}}{v_{flow}}$$

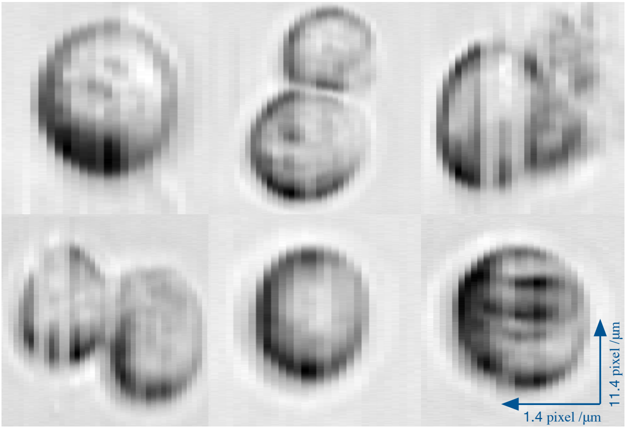
Variables	Denotation	Sample Value
Image Resolution (Horizontal)	$R_{horizontal}$	1.4 pixel/µm
Image Resolution (Vertical)	$R_{vertical}$	11.4 pixel/µm

~8x unbalanced H/V resolution

Unbalanced H/V Resolution



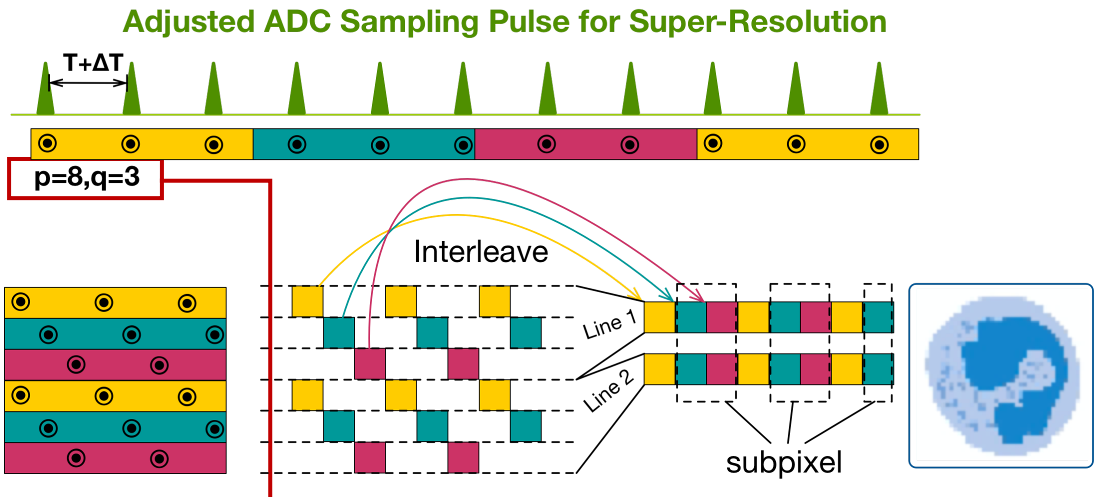
Demonstration of unbalanced H/V resolution image, image is sampled more tightly in vertical direction



MCF-7 (breast cancer cell) imaging with line-aligned sampling method, sampling frequency is 3.99 GHz. Jagged-edge is apparent in horizontal direction

- **How to optimize the sampling?**
  - **Method Constraints**
    - Only slightly adjust the ADC sampling frequency, but still sampling line scans uniformly
    - No computation overhead (complicate interpolation computation), because of the ultrafast throughput (4GB/s)
    - Acceptable data increment
  - **Method Assumption**
    - Combine several lines into one line
    - Different with line-aligned sampling, sampling points between lines should be shifted / interleaved

Super-resolution with Subpixel Shift



p, q are co-prime integers, represent sampling **p** points in **q** lines uniformly.

- **Adjust the sampling frequency (T to T+ΔT)**
  - Previous **line-aligned sampling:** 3 points per line (in previous example picture)
  - **Super-resolution sampling:** 8 points per 3 lines (in this example picture), not integer sampling points per line
  - new **co-prime** parameters: **{p, q}**
- **Interleave samples of every q lines to one super-resolution line**
  - Interleave pattern repeats every **q** lines
  - In the example picture, **horizontal** resolution will be ~3x **higher** (with the subpixels); **vertical** resolution will be ~3x **lower**

Super-resolution Sampling

- **Relations of parameters in super-resolution sampling**
  - Sampling frequency is decided by **{p, q}** and laser frequency, also should be constrained at ~4GHz.
  - **q** decides spatial line number that used to generate the super-resolution line. Case **q=1** is equivalent to the normal line-aligned sampling
  - Hence, **p** is a proper number that constrained by **q** and sampling / laser frequency.

$$f_{sampling} = f_{laser} \times p/q$$

$$R_{horizontal} = \frac{p}{Width}$$

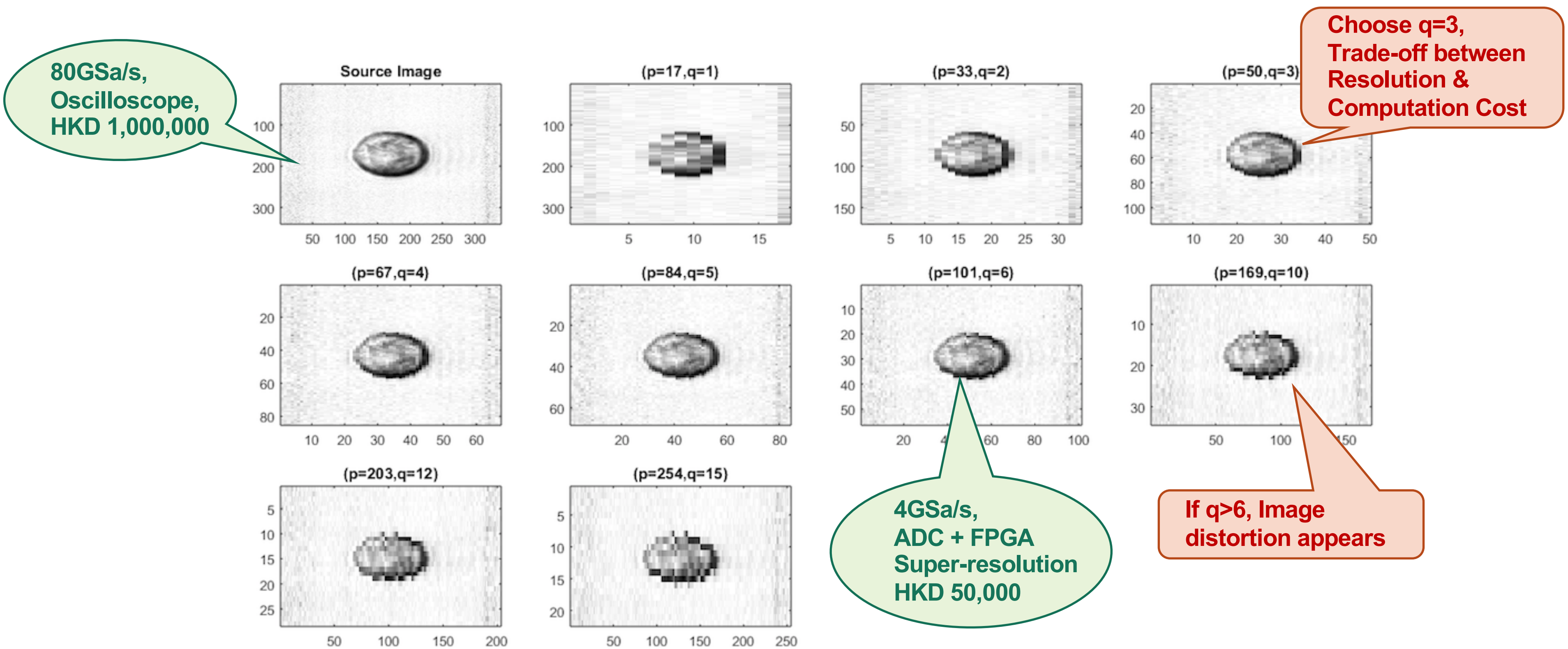
$$R_{vertical} = \frac{f_{laser}}{v_{flow} \times q}$$

Parameters	Previous	Super-resolution
p, q	350,1	**1024, 3**
$f_{sampling}$	3.99 GHz	3.89 GHz
$R_{horizontal}$	1.4 pixel/μm	4.1 pixel/μm
$R_{vertical}$	11.4 pixel/μm	3.8 pixel/μm

- **Next Step:** Choose a proper **q**

Evaluation of different {p, q}

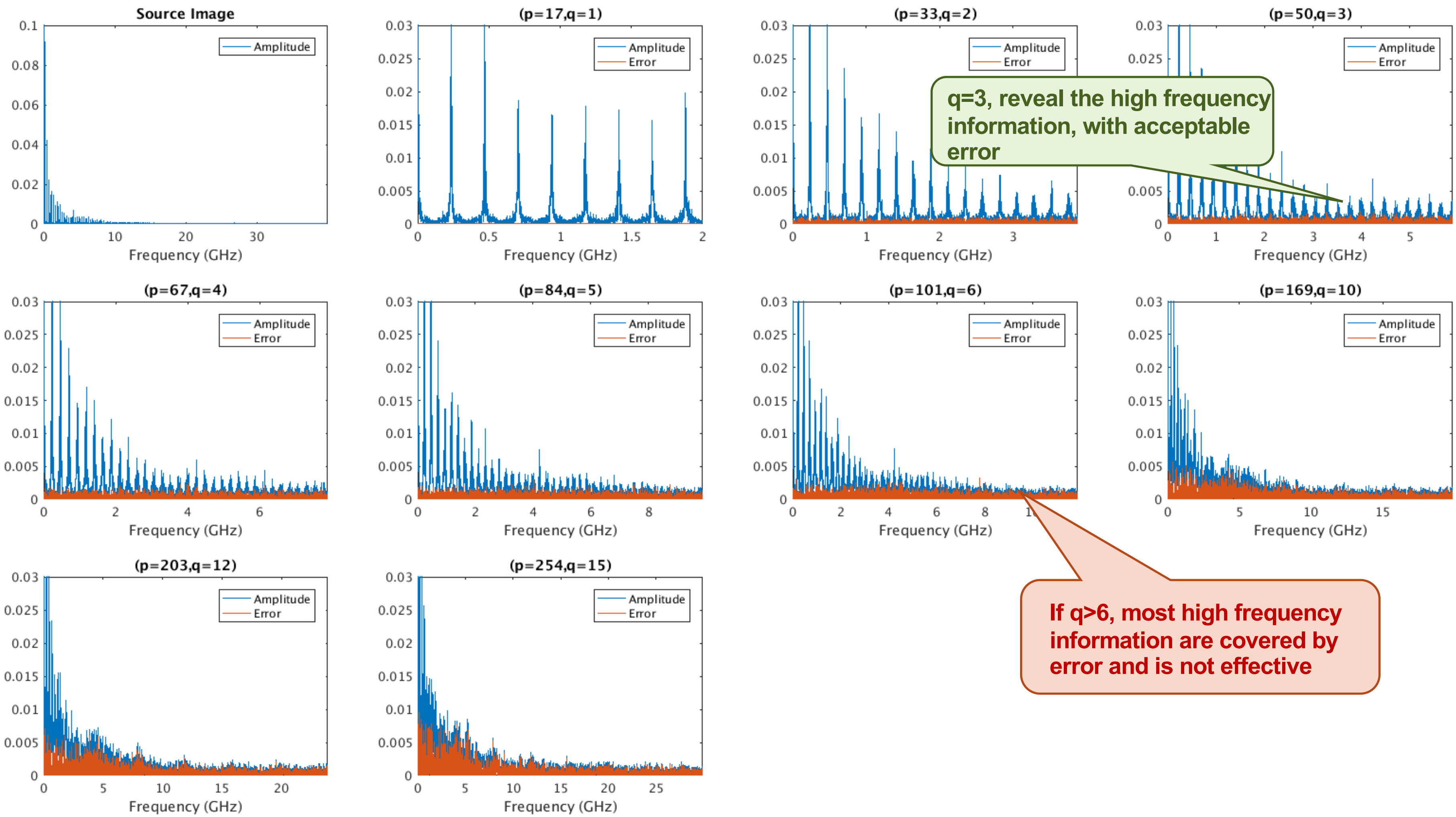
- **Sampling simulation with different {p, q}**
  - **Motivation of this evaluation:** Choose a proper **q** value
  - Source image: sampled with **80GSa/s oscilloscope,** crop the cell area, **340** pixel/line
  - **Down-sampling** the image ~20x to ~4GSa/s, ~17 sample points / line, (**p/q≅17**)
    - Reshape the 2D image to a whole line and do **1D down-sampling**
    - Case **{p=17, q=1}** is the normal line-aligned sampling
    - The other cases are super-resolution with subpixel shift, with different **{p, q}** set, similar sampling frequency



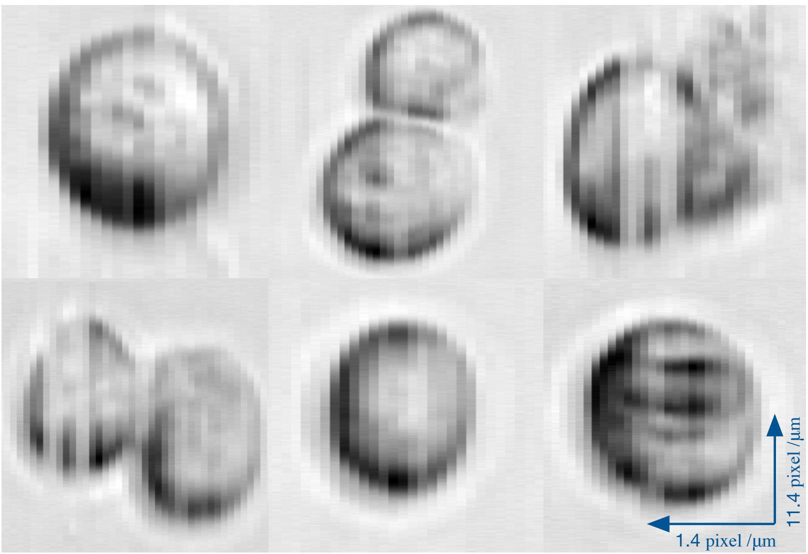
Frequency Domain Analysis

- **Analyze the previous simulation results in frequency domain**
  - **Motivation of the analysis:**
    - Verify that the high frequency information is revealed by the super-resolution (make cell texture clearer)
    - Evaluation the error that introduced by the sub-pixel shift (theoretically error increase as the **q** becomes bigger)
  - **Fourier Transform in analysis**
    - Firstly, reshape the 2D image to a whole 1D line
    - 1D Fourier Transformation to 1D frequency domain, because the image is sampled line by line
  - **Based on Nyquist-Shannon sampling theorem**
    - MAX frequency in source image = 40 GHz (sampling frequency is 80 GHz)
    - MAX frequency in line-aligned sampled image (q=1) = 2 GHz (sampling frequency is 4 GHz)
    - MAX frequency in image with super-resolution = 2***q** GHz (With the super-pixels, we assume the equivalent sampling frequency increases)
  - **Error Analysis**
    - Replace the shifted sub-pixels with the original ones in the corresponding position of source image
    - Do the same Fourier Transform to get accurate frequency domain information
    - Calculate the error introduced by sub-pixel shift

Frequency Analysis Results



Experiment Results



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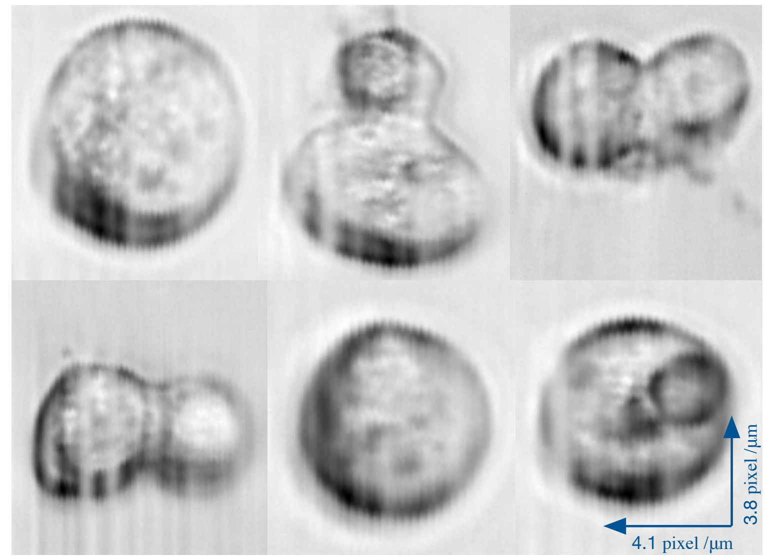

MCF-7 imaging with the proposed super-resolution method, sampling frequency is 3.89 GHz.

Parameters	Value	Variable	Value
p, q	350, 1	$R_{horizontal}$	1.4 pixel/μm
$f_{sampling}$	3.99 GHz	$R_{vertical}$	11.4 pixel/μm
Interleave	No		

Parameters	Value	Variable	Value
p, q	1024, 3	$R_{horizontal}$	4.1 pixel/μm
$f_{sampling}$	3.89 GHz	$R_{vertical}$	3.8 pixel/μm
Interleave	Yes		

Summary & Future Work

- **Super-resolution in cellular imaging**
    - Slightly adjust the sampling frequency
    - No sampling data increment
    - Acceptable interleave computation
    - Obvious image quality improvement
- **Future Work**
    - Proper interpolation to eliminate the jagged edge

Thanks.