Accurate and Fast Testing Technique of Operational Amplifier DC Offset Voltage in μV-order by DC-AC Conversion

The 3rd International Test Conference in Asia, 2019

Gunma University

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Purpose

To achieve high accuracy and fast testing of very small DC voltage with Automatic Test Equipment (ATE)

- Requirements
  - μV-order Testing
  - Fast Testing

- **Proposed Method**

  FFT-Based DC-AC Conversion

Outline

- **Background and Motivation**
  - Conventional Test Method
  - Difficulty for μV-order Testing
- **Proposed Method**
  - FFT-Based DC-AC Conversion
  - Challenge for Multi-Site Testing
- **Conclusion**

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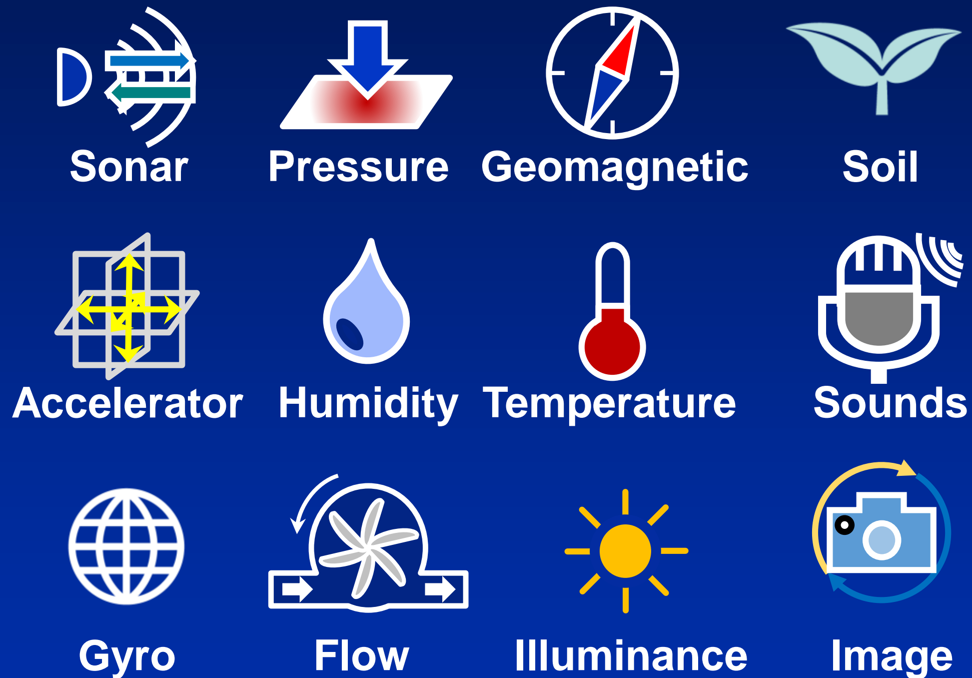
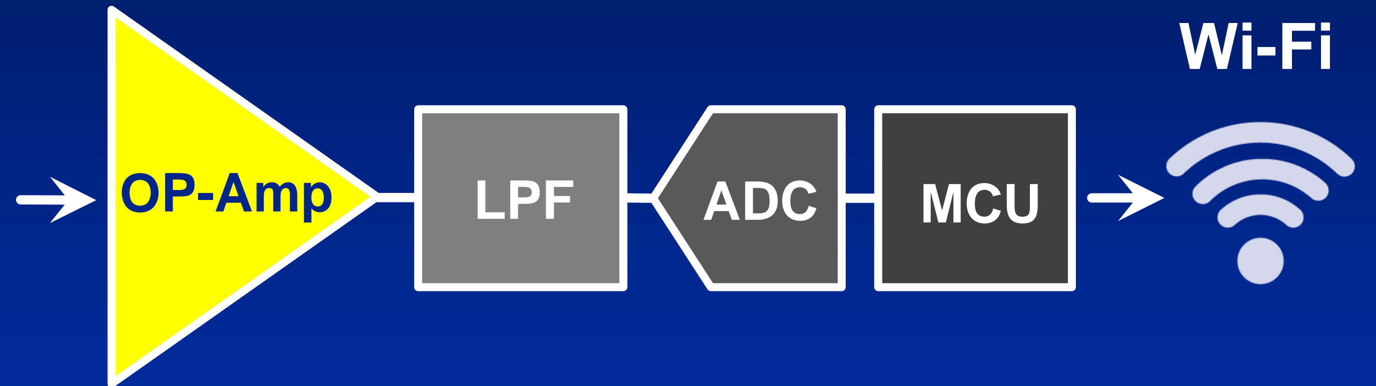
Background

IoT Sensor Network

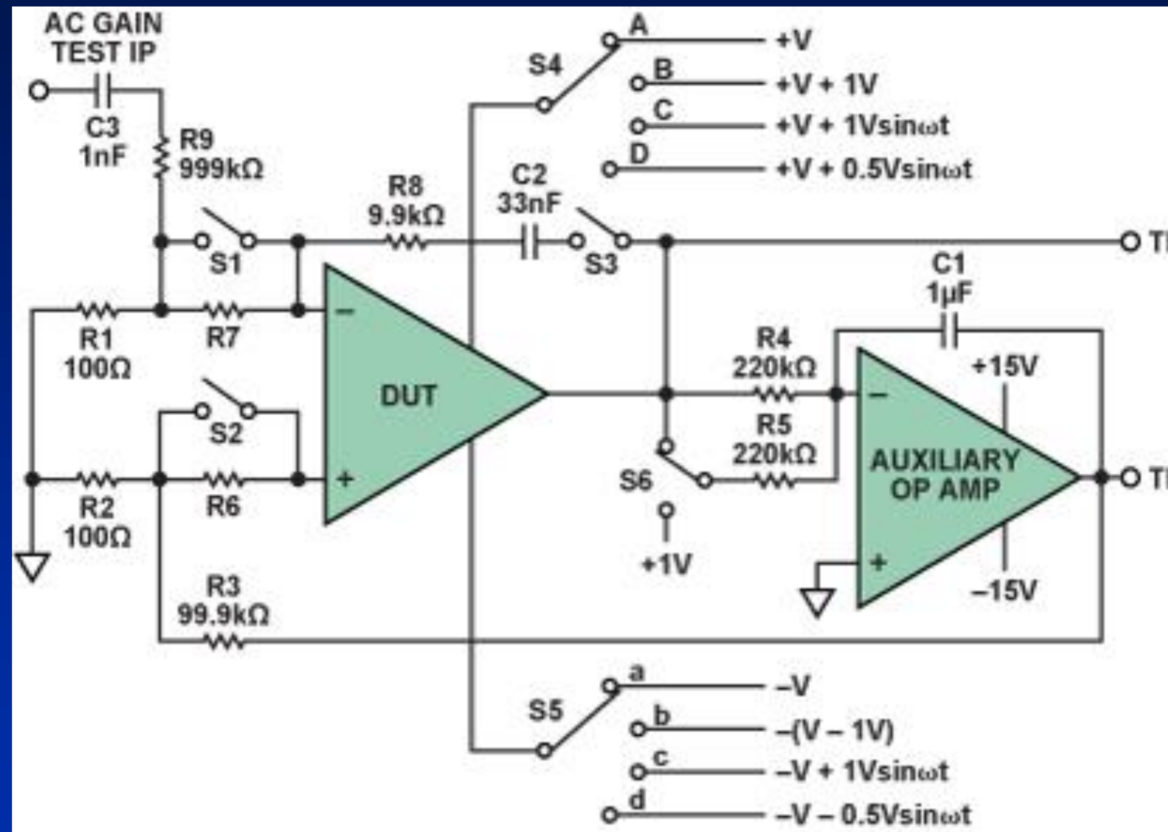




μV-order offset OP-Amp is a key component of IoT system

Conventional Test Method (1)

Null Method for OP-Amp Test Circuit



[1] James M. Bryant, "Simple Op Amp Measurement", Analog Dialogue, vol.45, pp 21-23 (2011)

Conventional Test Method (2)

Usage of High Accuracy Digital Multimeter

KEYSIGHT 3458A   8 ½ Digit

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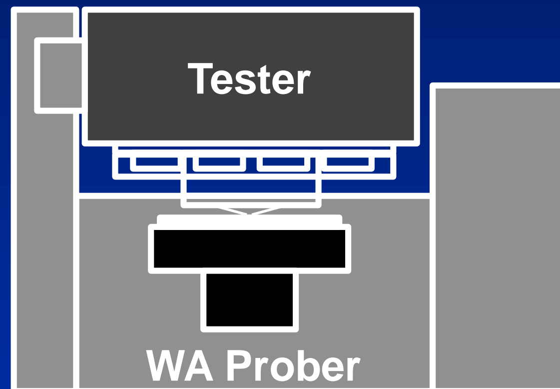
Difficulty for μV-order Testing

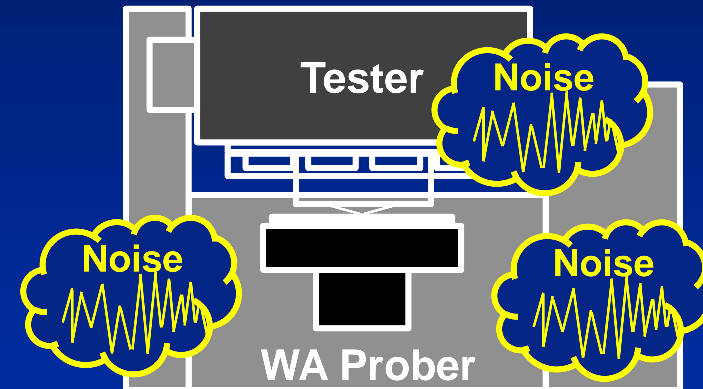
⚠ Problem

1. Noise at Test Environment

Test Environment



Actual Situation



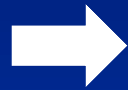
System noises affect μV-order Testing

Difficulty for μV-order Testing (Cont’d)

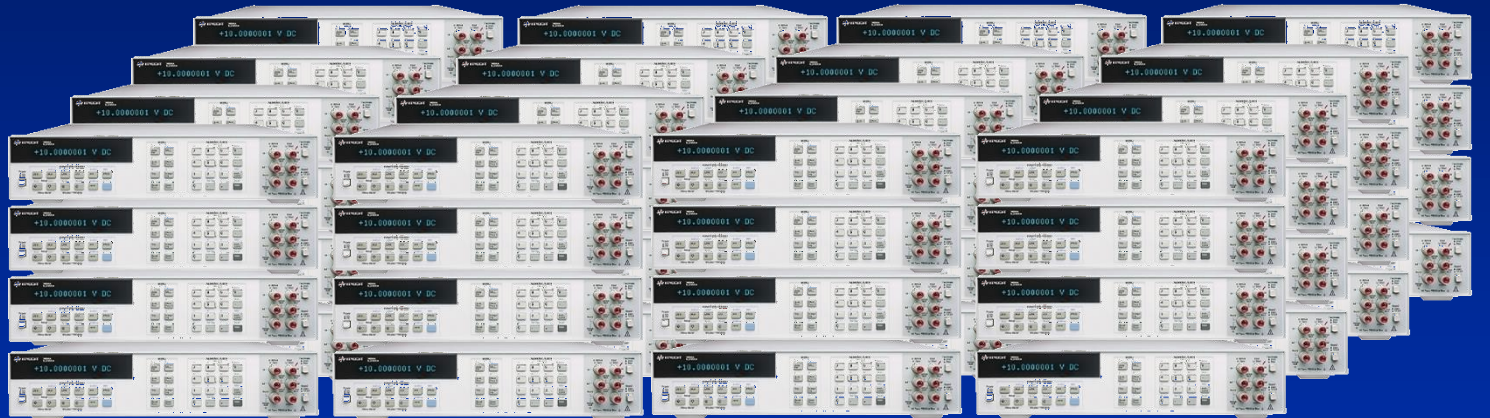
⚠ Problem

2. Test Time (Multi-Site)

Single



Multi

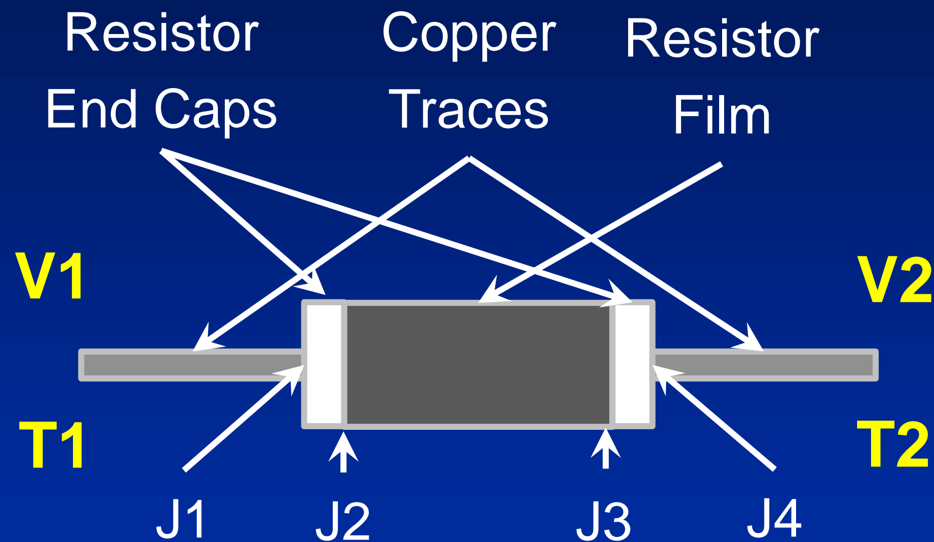


Unrealistic Situation

Difficulty for μV-order Testing (Cont'd)

⚠ Problem

3. Electromotive Force (EMF)



V1, V2 : Voltage

T1, T2 : Temperature

J1, J2, J3, J4 : Contact of different metals

Vemf : Difference btw V1 and V2

EMF of Metal Film Resistance: 30 μV/℃

Vemf = V1 – V2 = 30 μV * (T1 - T2)   ;T1>T2

Keep temperature difference small enough

Motivation

To Solve Problems

1. Noise at Test Environment

Testing ➡ NOT affected by **system noises**

2. Test Time

Testing method ➡ Applicable to **multi-site testing**

3. Electromotive Force (EMF)

Temperature difference ➡ **Less than 0.1 ℃** for μV-order testing

To Propose μV-order Test Method for ATE

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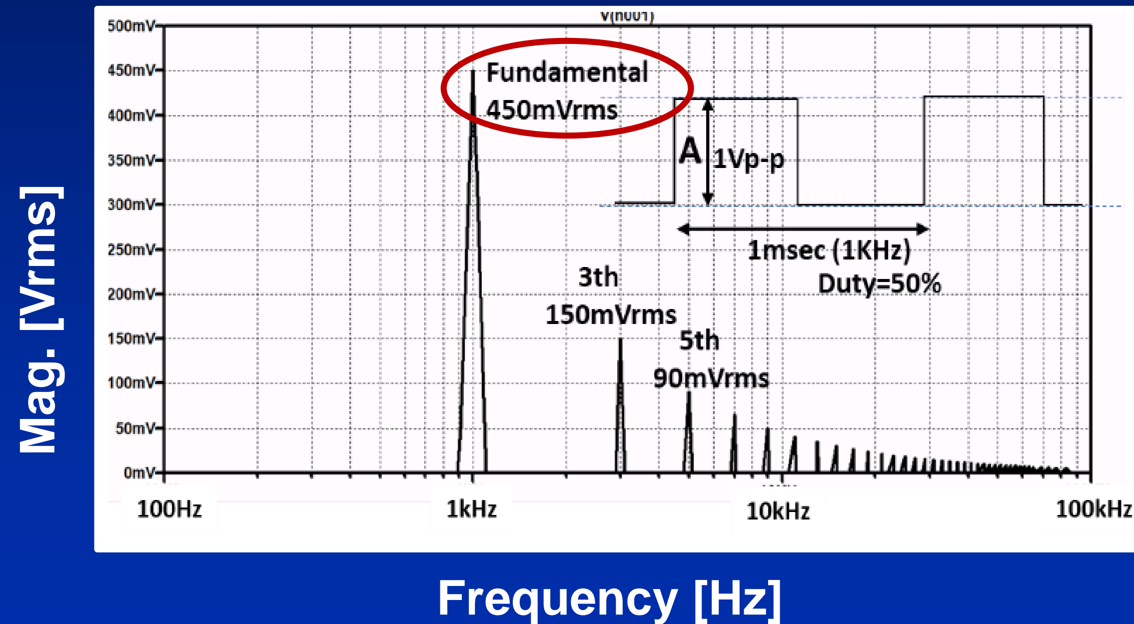
Proposed Method

FFT-Based DC-AC Conversion

DC Voltage ➡ AC Square Wave ➡ Fast Fourier Transform

$$V(t) = \frac{2A}{\pi}\left(\sin\omega t + \frac{1}{3}\sin 3\omega t + \frac{1}{5}\sin 5\omega t + \cdots\right)$$



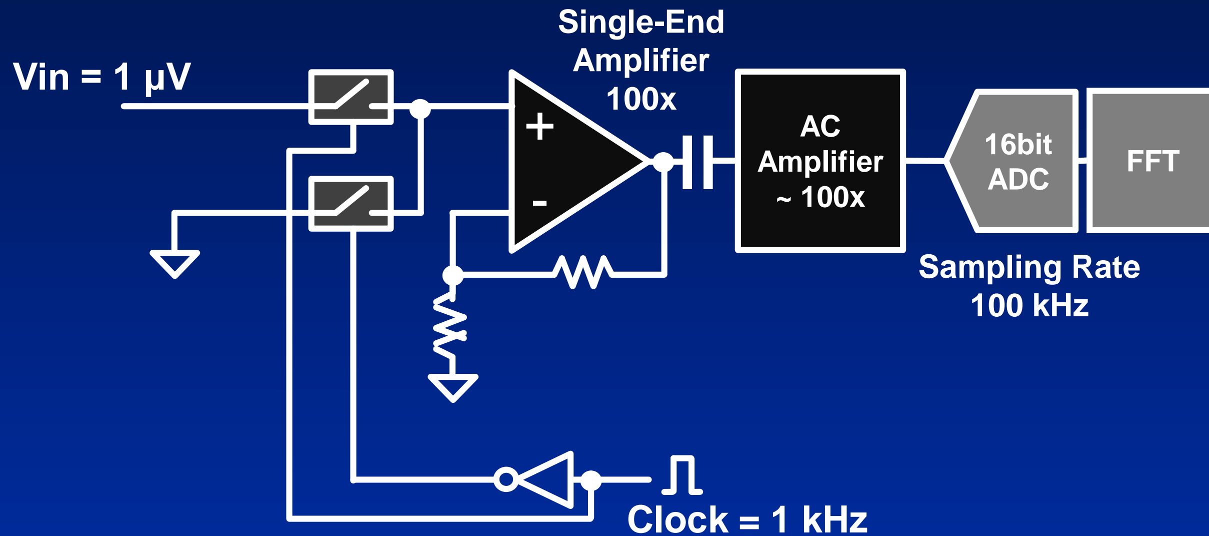
Mag. [Vrms]

Frequency [Hz]

DC Voltage is converted to Fundamental Power Spectrum

FFT-Based DC-AC Conversion (Simulation)

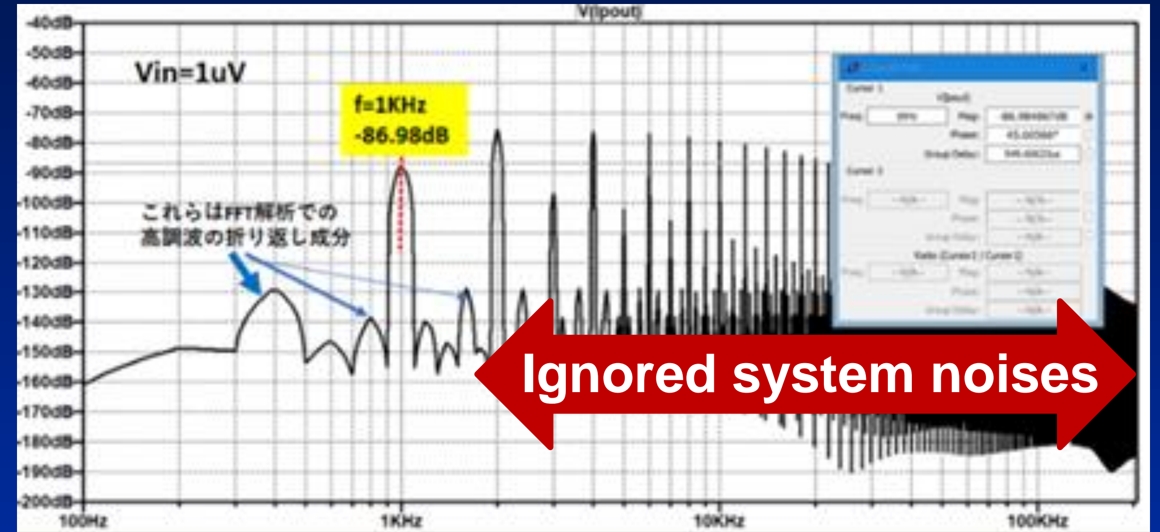
DC-AC Conversion Circuit



DC-AC Conversion Clock: 1 kHz (duty 50 %)

CMOS Switch: Nch FET (2N4393)

FFT Result



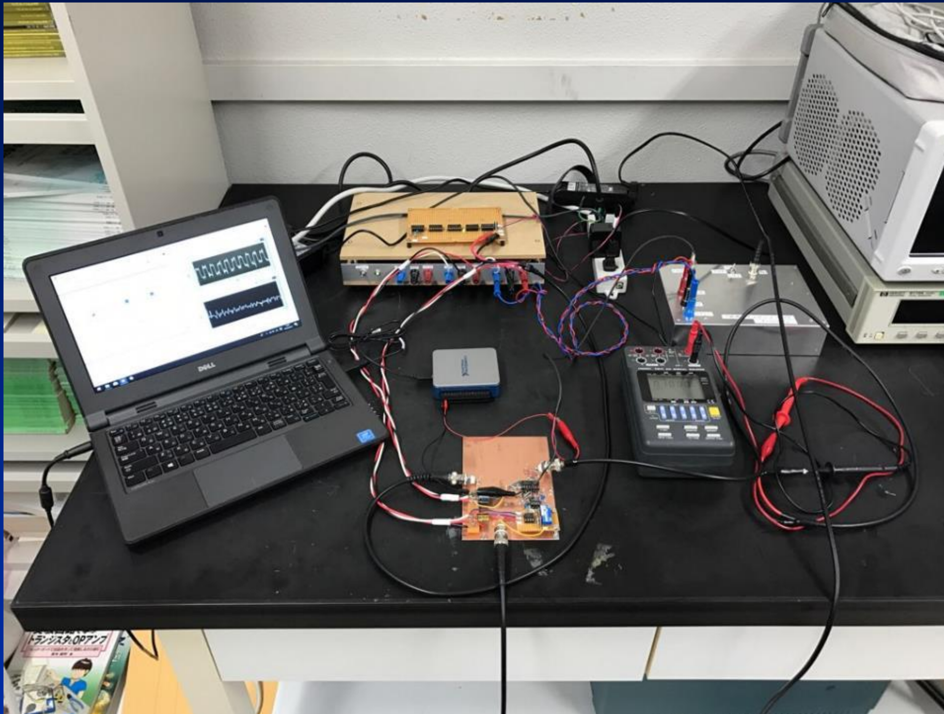
LTspice FFT Condition:

Fs = 409.6 kHz, Fres = 100 Hz, N = 4096, Rectangle Window

- ✓ **Measurement as low as 1 nV is possible, based on simulation**
- ✓ **Thanks to FFT, system noises can be ignored**

FFT-Based DC-AC Conversion (Initial Experiment)

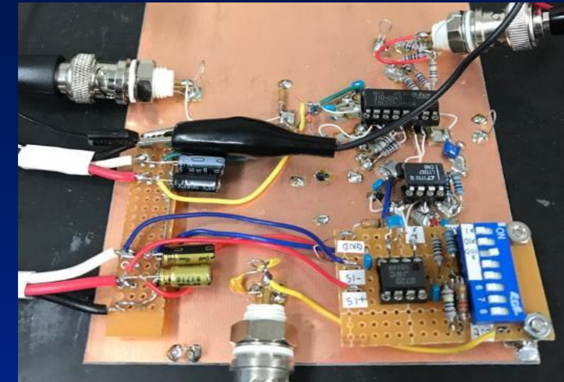
Experiment Environment



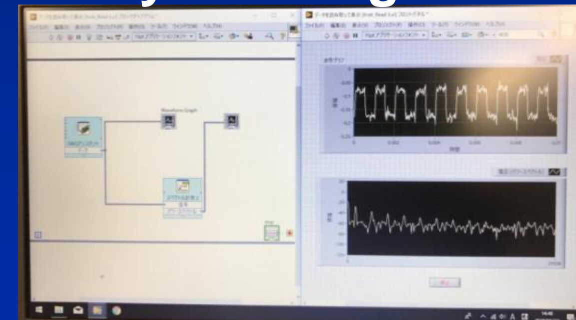
Switch: CMOS Analog SW IC (4053)

Environment
- LabVIEW
- NI USB-6001/6002/6003 (16 bit ADC)

DC-AC Conversion

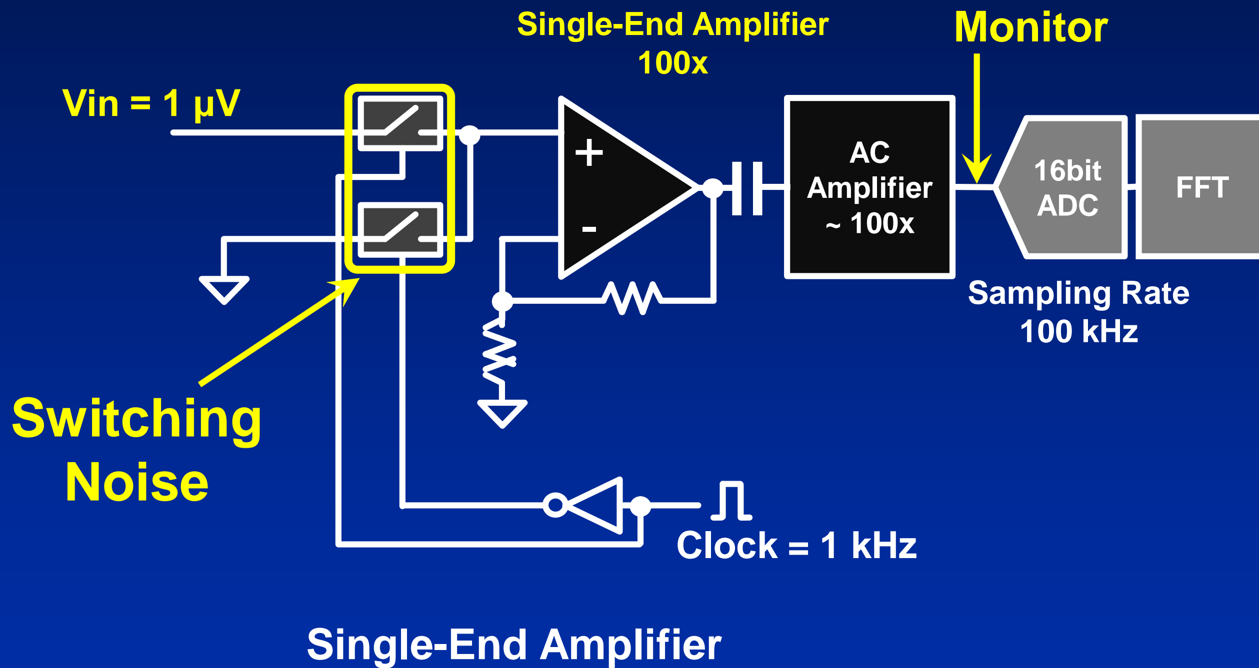


Analysis using LabVIEW



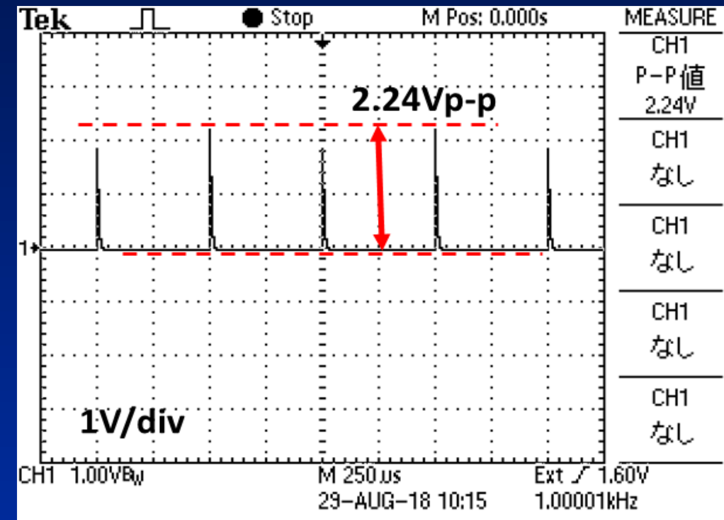
Switching Noise Problem

Initial Circuit



Single-End Amplifier

Monitor



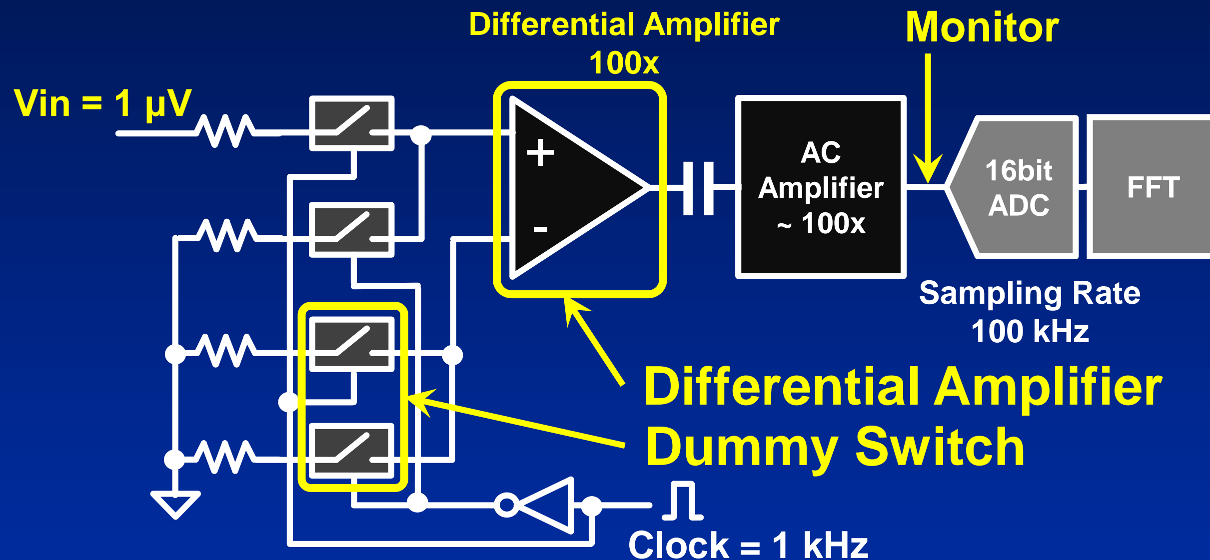
Switching Noise

Consideration of Differential Amplifier Usage

Switching Noise Countermeasure

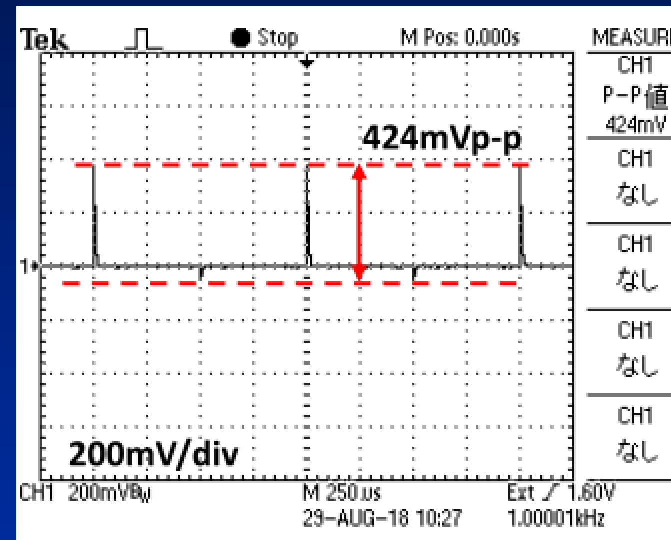
Effect of Switching Noise w/ Countermeasure

Improved Circuit



Differential Amplifier (Add Dummy Switch)

Monitor



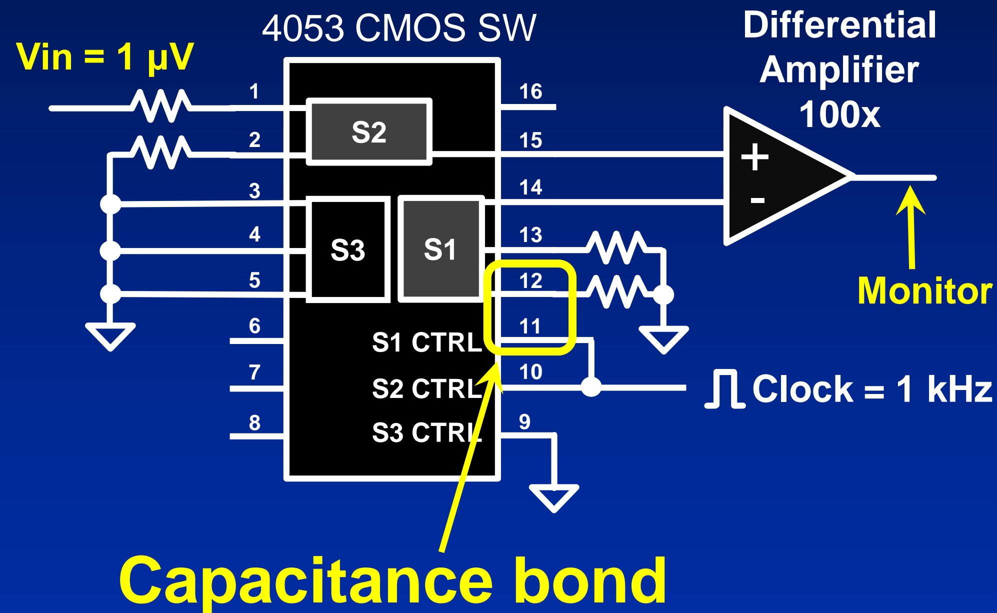
Switching Noise

Switching noise is reduced to 1/5

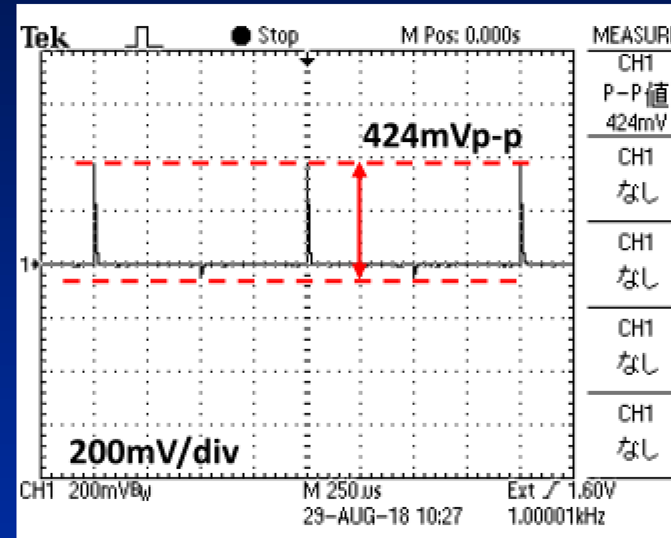
Switching Clock Leak Problem

Affect of Switching Clock Leak

Initial Circuit



Monitor



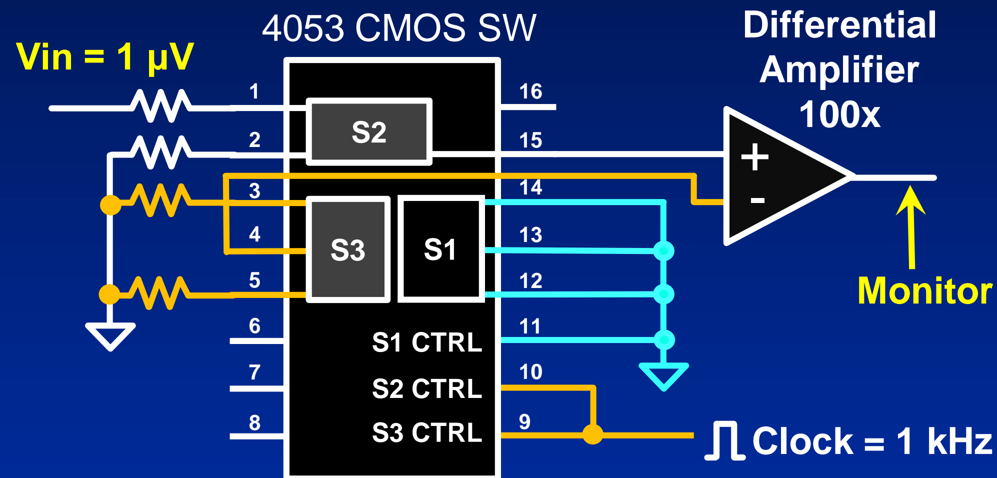
Switching Noise

Parasitic capacitance btw Pin and Pin affect switching clock leak

Switching Clock Leak Countermeasure

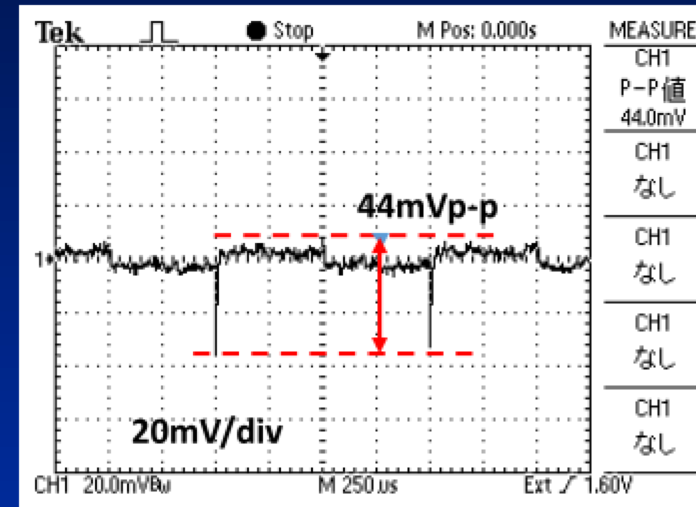
Affect of Switching Clock Leak w/ Countermeasure

Improved Circuit



Use of S3 instead of S1

Monitor

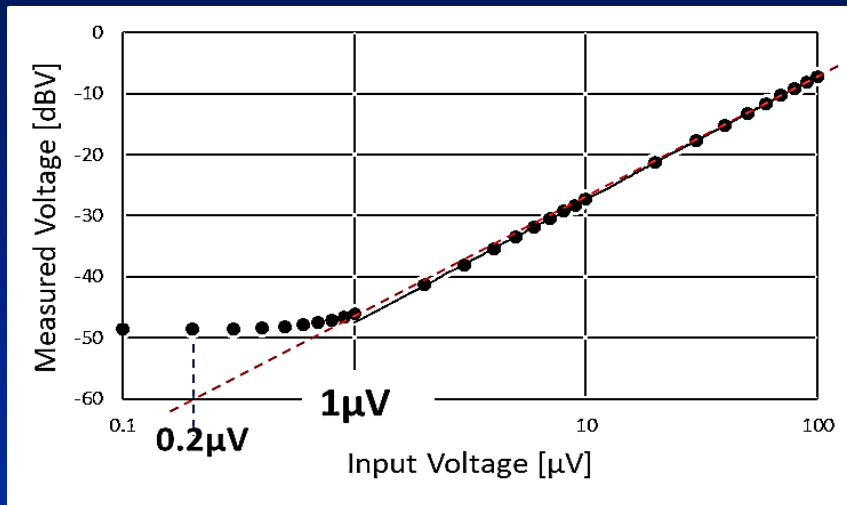


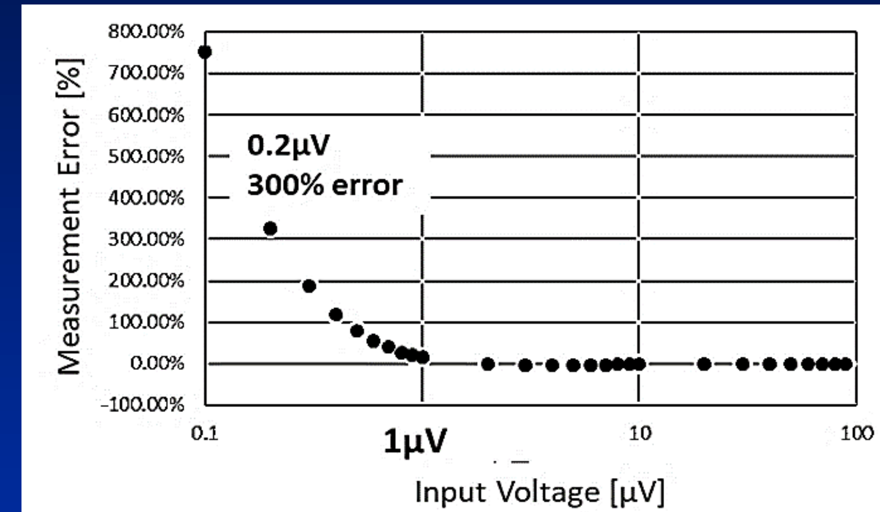
Switching Noise

Switching noise is reduced to 1/10

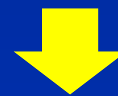
Measurement with Both Countermeasures

Sampling Rate: 100 kHz, Sample: 10 k, Averaging: 100, Frequency Resolution: 10 Hz





it's possible to measure as low as 2 μV

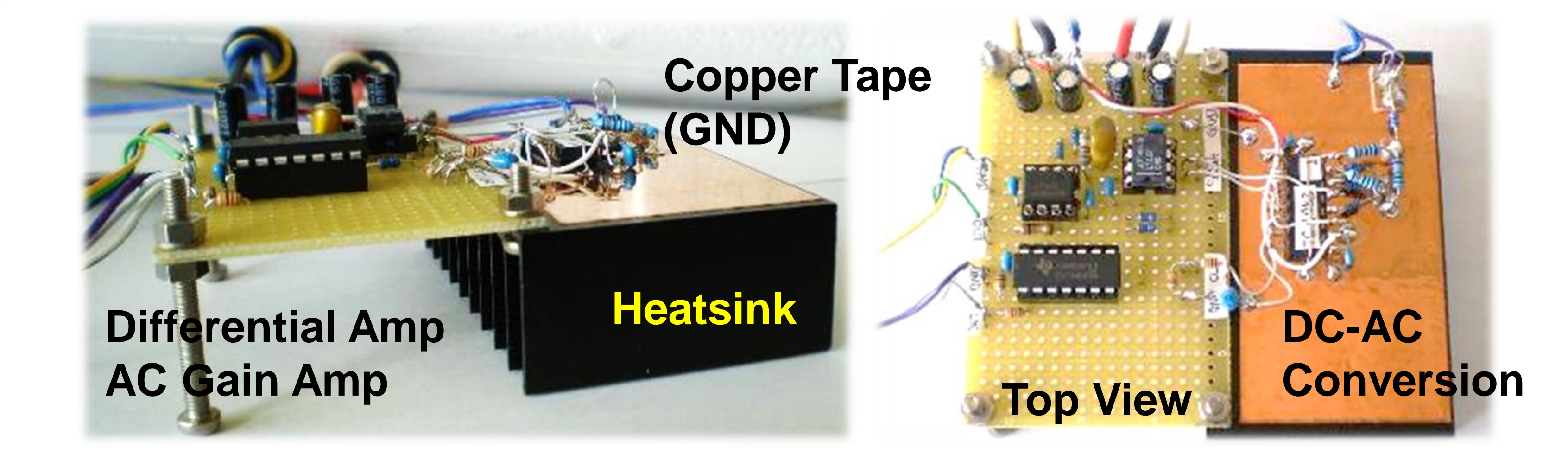


EMF countermeasure is essential for further performance

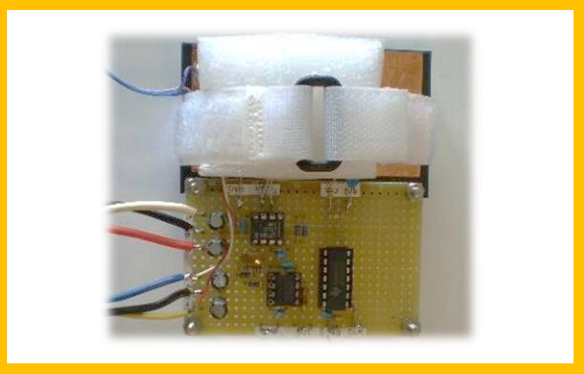
Electromotive Force (EMF) Countermeasure

EMF Countermeasure

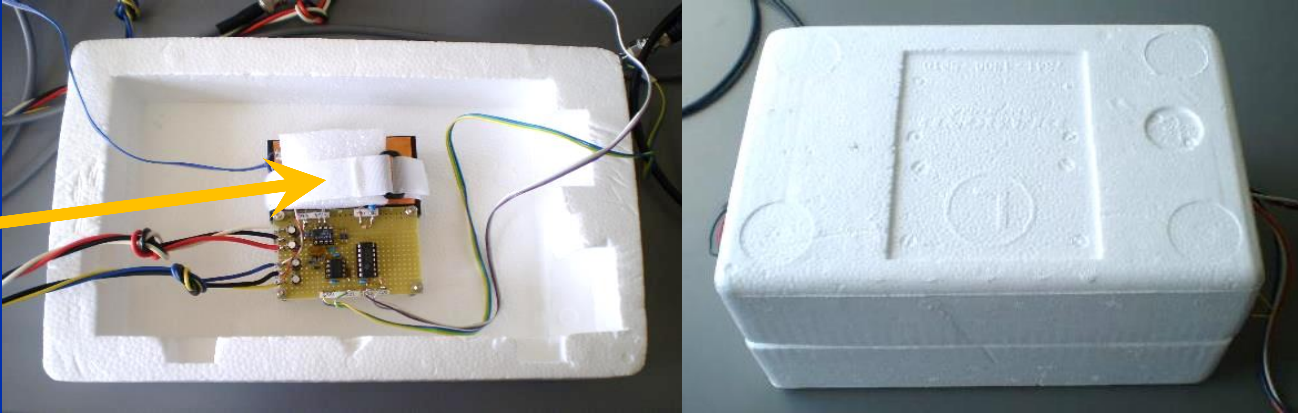
Upside down Switch IC (4053) contact Heatsink via Copper Tape (GND)



Switch IC (4053) is covered by Styrofoam



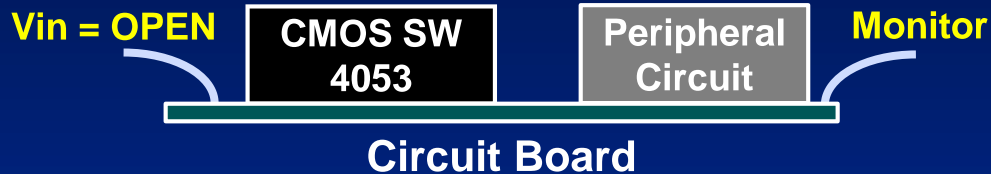
Styrofoam Box

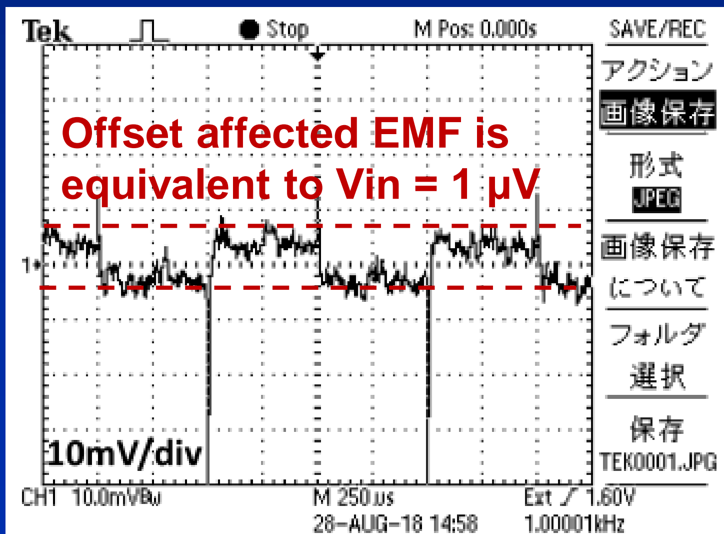


EMF Countermeasure Effectiveness

EMF Countermeasure

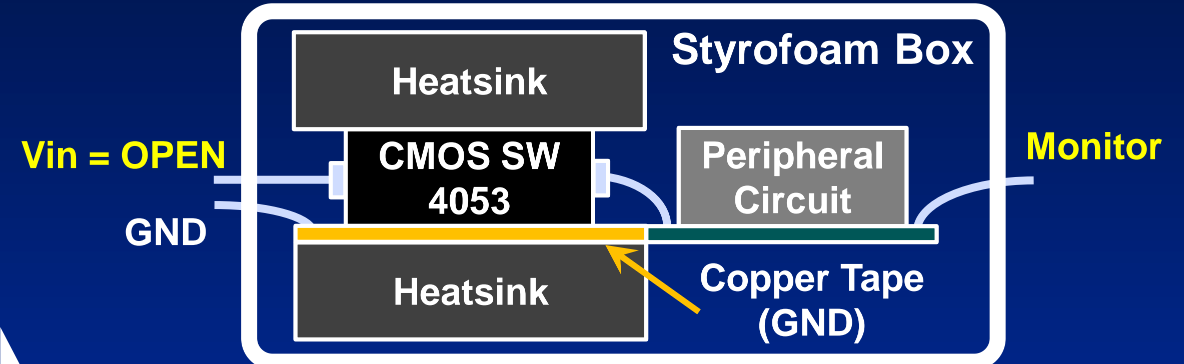
Initial Condition (Exposed in atmosphere)

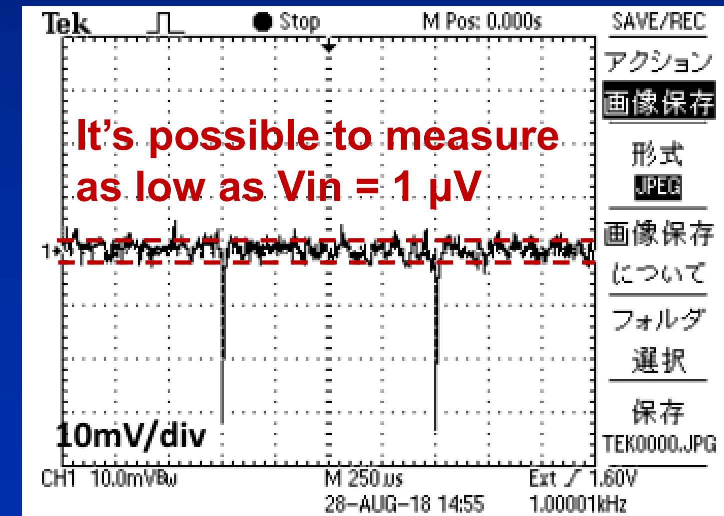




EMF affects output

Improved Condition (Constant Temperature)





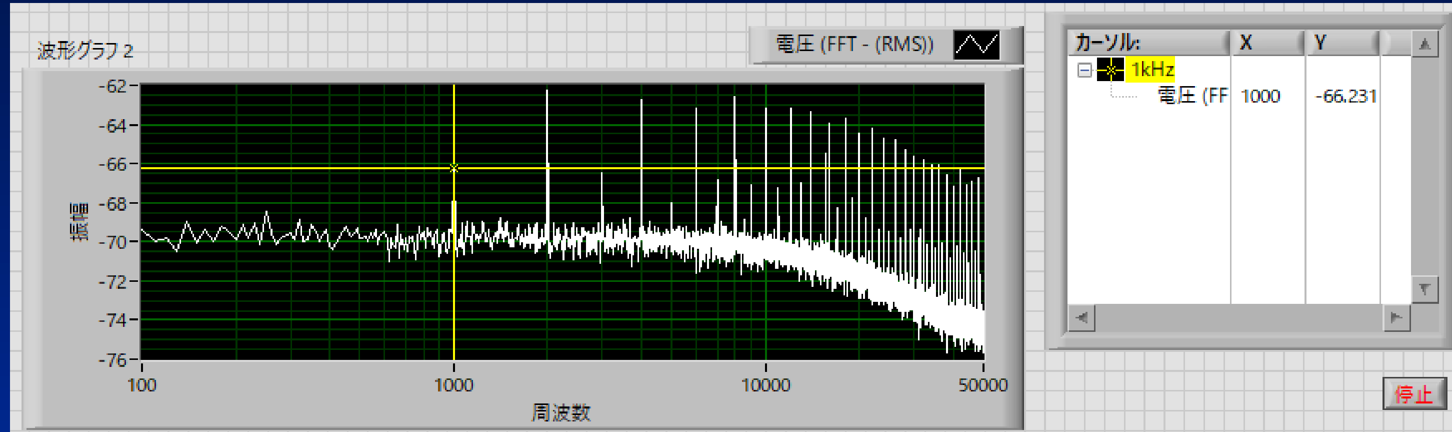
Significant Improvement

Power Spectrum with All Countermeasures

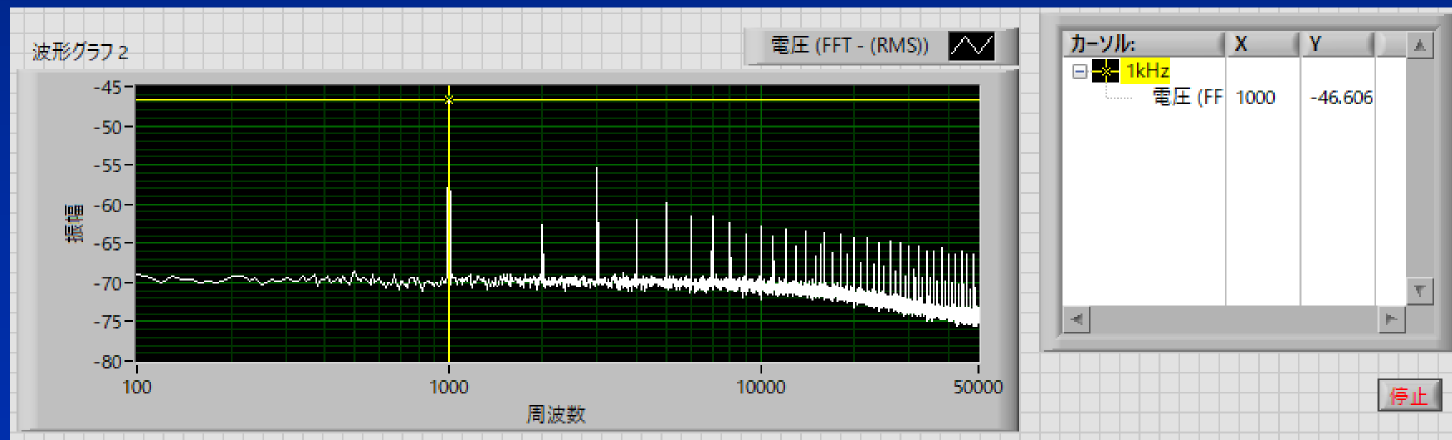
Improved Result

Sampling Rate: 100 kHz, Sample: 10 k, Averaging: 100, Frequency Resolution: 10 Hz

Vin = 0 μV



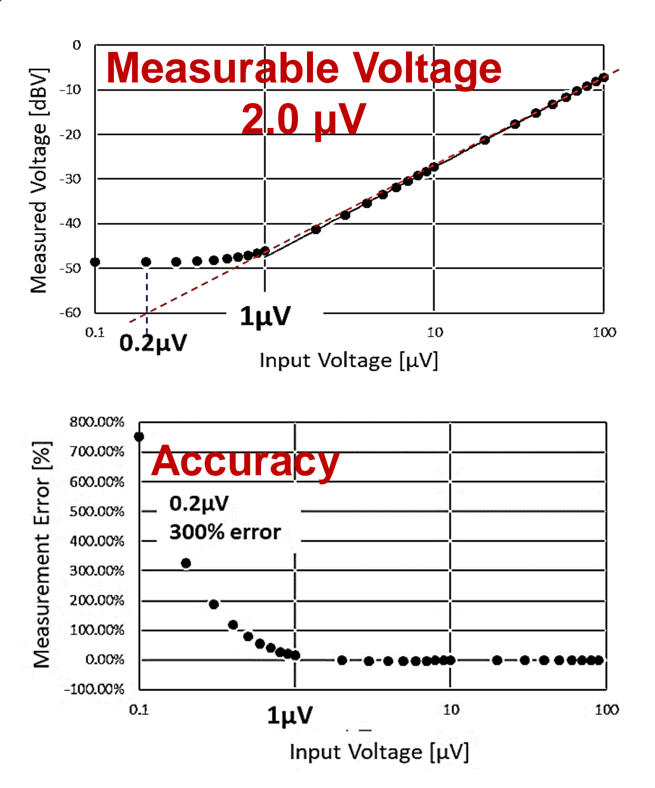
Vin = 1 μV

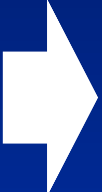


it's possible to measure 1 μV

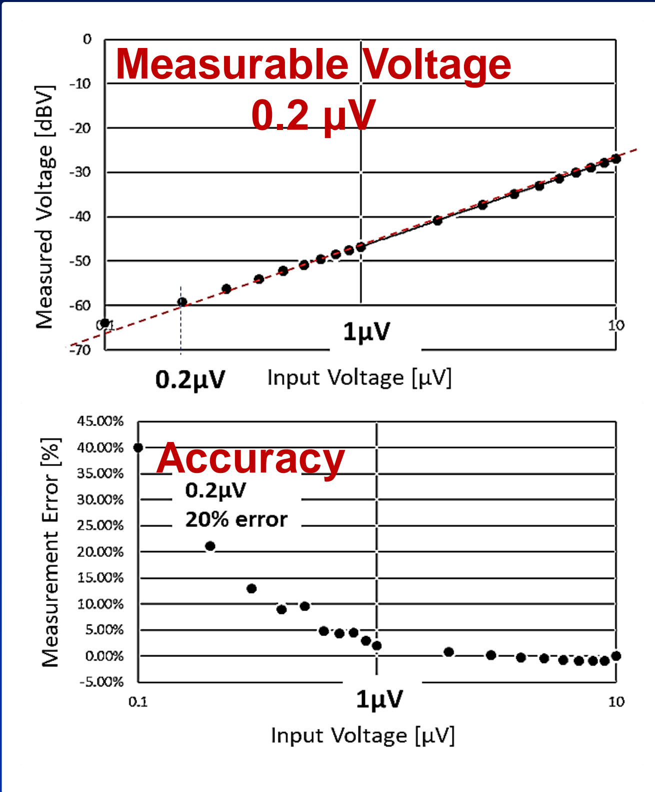
Measurement with All Countermeasures

Low voltage measurement w/o EMF Countermeasure





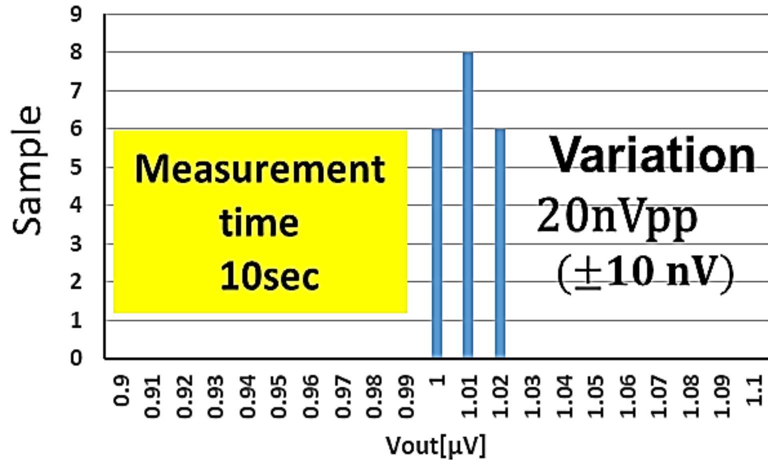
Low voltage measurement w/ EMF Countermeasure



Linearity is improved

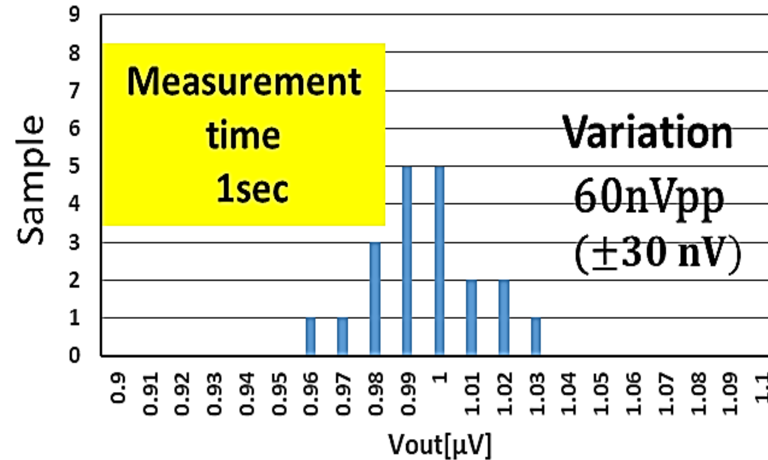
Variation and Repeatability of Measurement

100ksps,10kpoint, Average 100x



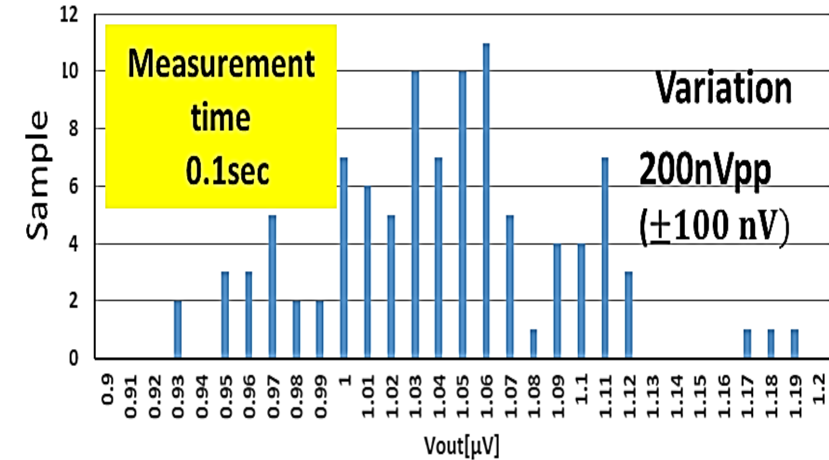
Accuracy 1μV ± 1 %

100ksps,10kpoint, Average 10x



Accuracy 1μV ± 3 %

100ksps,10kpoint, Average 1x



Accuracy 1μV ± 10 %

Dependent on the number of averages

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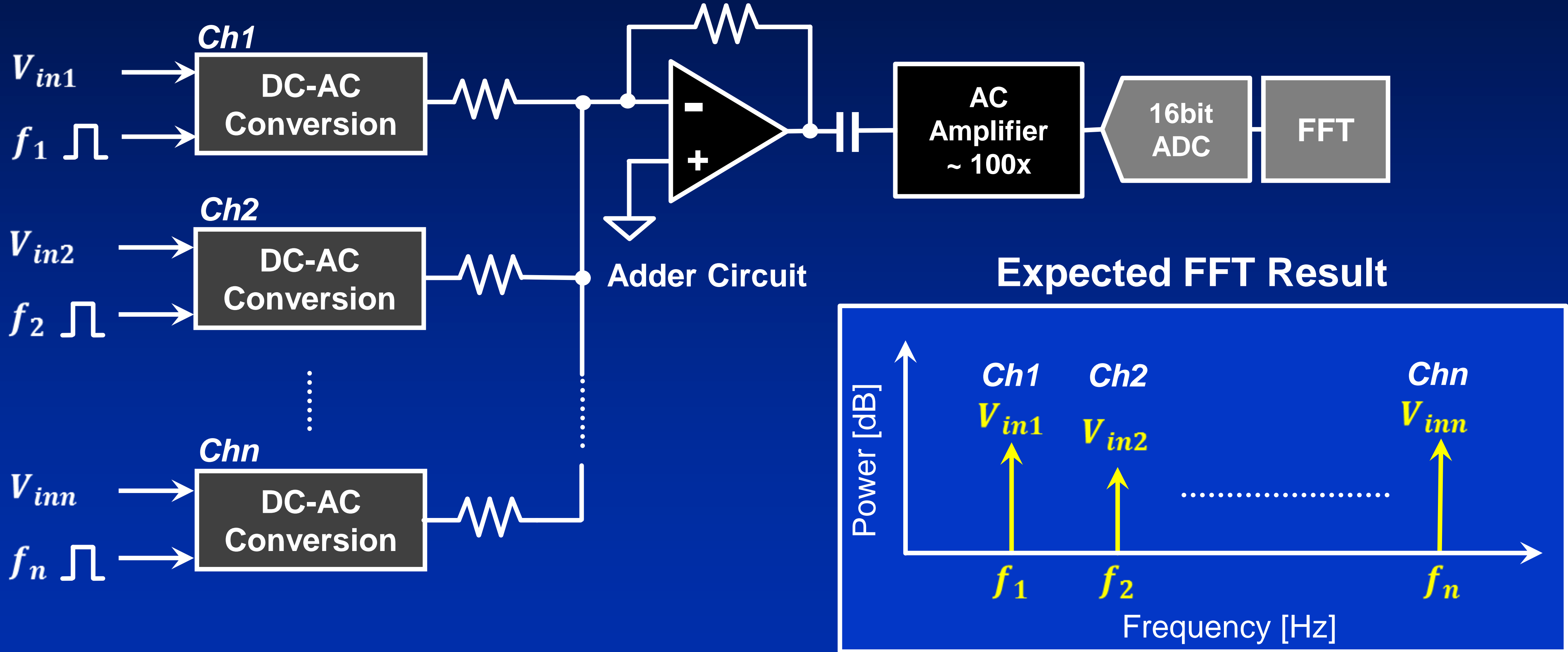
FFT-Based DC-AC Conversion for Multi-Site Testing

Configuration & Operation



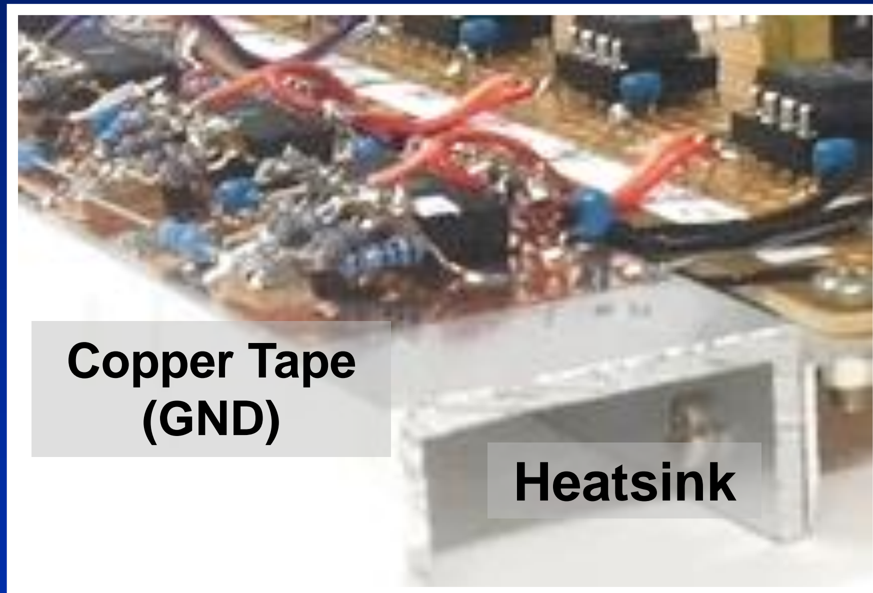
Multi-site testing is possible

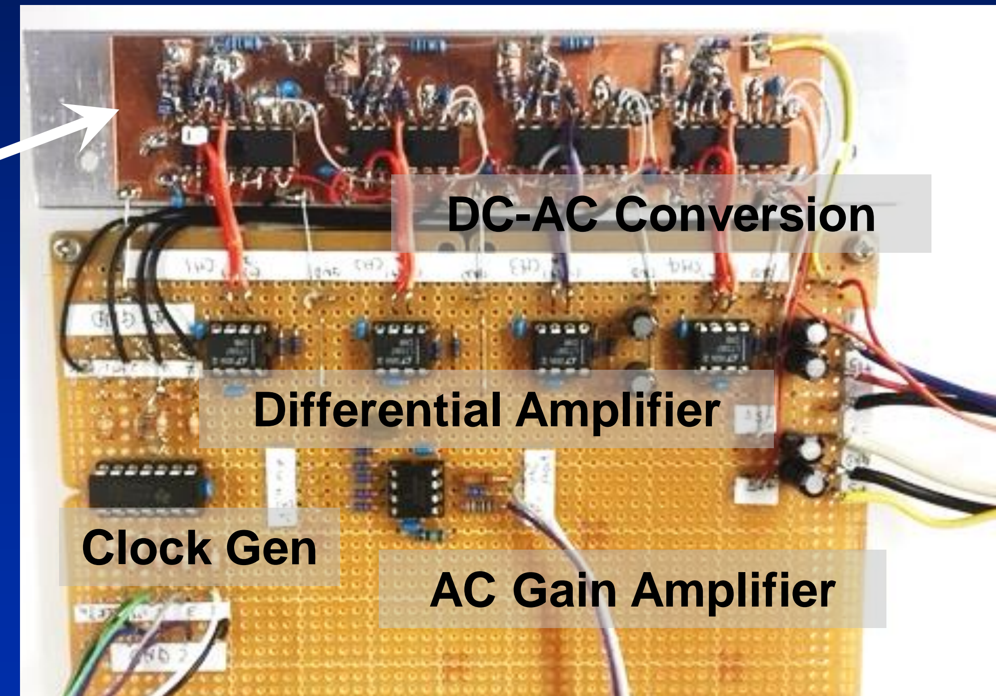
Experiment Environment for Multi-Site Testing

Four-Site case

Upside down Switch IC (4053) contact Heatsink via Copper Tape (GND)

DC-AC Conversion Part





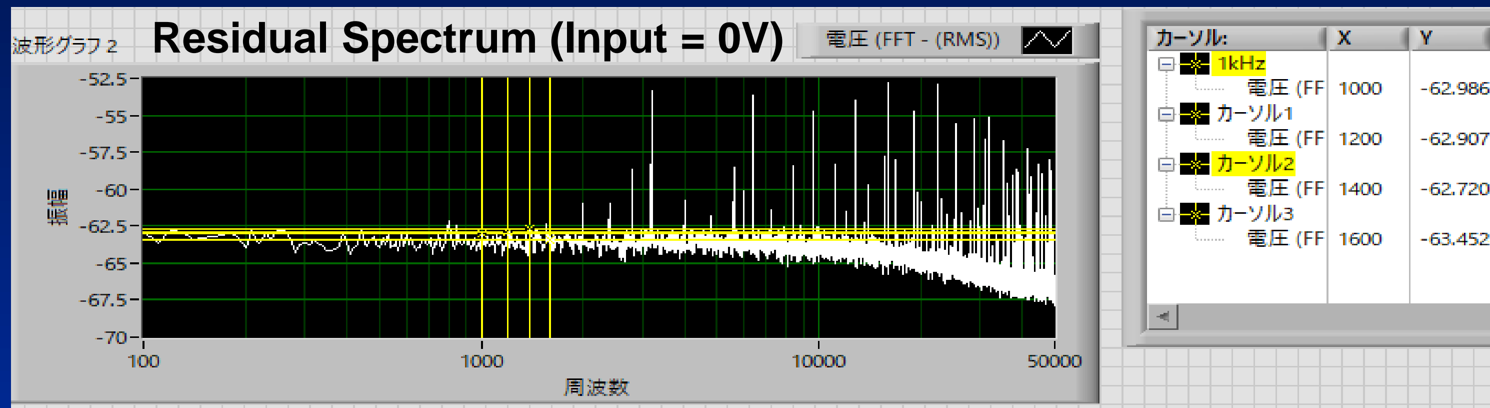
Verification with Spectrum Measurement

Four-Site Testing Measured Spectrum

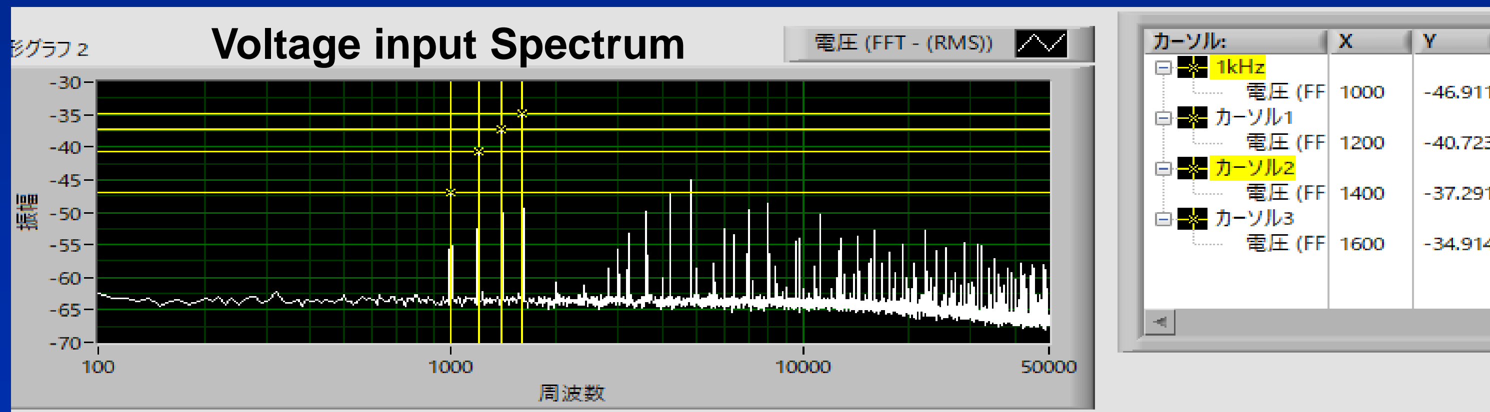
Sampling Rate: 100 kHz , Sample: 10k, Averaging: 100, Frequency Resolution: 10 Hz

Ch1 =1.0 kHz, Ch2 = 1.2 kHz, Ch3 = 1.4 kHz, Ch4 = 1.6 kHz

Vin1 = 0 V
Vin2 = 0 V
Vin3 = 0 V
Vin4 = 0 V



Vin1 = 1 μV
Vin2 = 2 μV
Vin3 = 3 μV
Vin4 = 4 μV

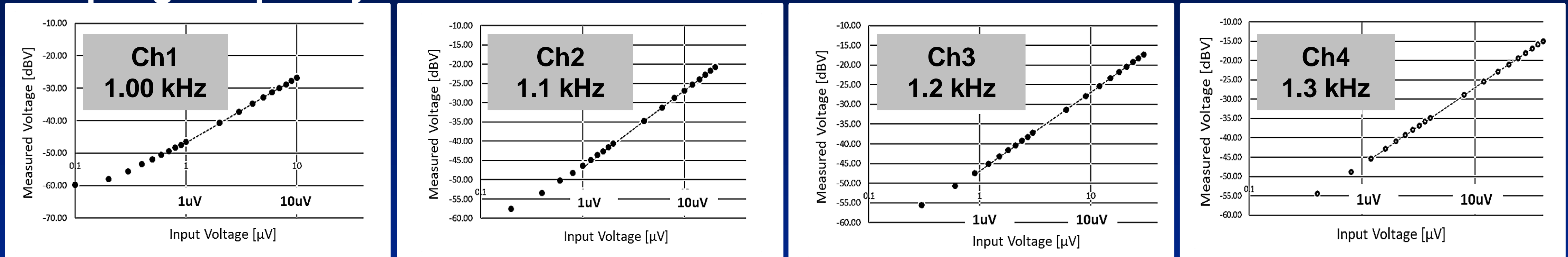


Multi-site testing is applicable

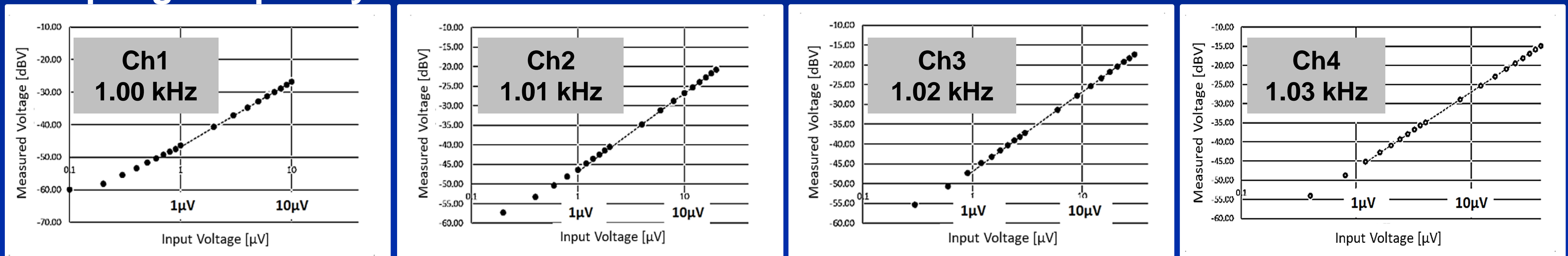
Verification with Linearity Measurement

Four-Site Testing

Sampling Frequency Interval: 0.1 kHz



Sampling Frequency Interval: 0.01 kHz



Four-site measurement as low as 0.2 µV is possible

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Conclusion

Solved Problems

1. Noise at Test Environment

Testing is NOT affected by system noises

2. Test Time

Testing method is applicable to multi-site testing

3. Electromotive force (EMF)

Keep temperature difference less than 0.1 ℃ for μV-order testing

Proposed FFT-based DC-AC conversion is applicable for μV-order test using ATE

Q&A

- Is the EMF Seebeck effect?
  – Yes.

- How about a throughput of the test? It seems to need a time for steady temperature of changed DUT against EMF.
  – No problem because temperature of test environment is under control. In addition, temperature difference is no effect except between regsistors in a DC-AC conversion circuit.