STu1F.4

Real-Time Absolute Frequency Measurement of CW-THz Wave Based on Dual THz Combs

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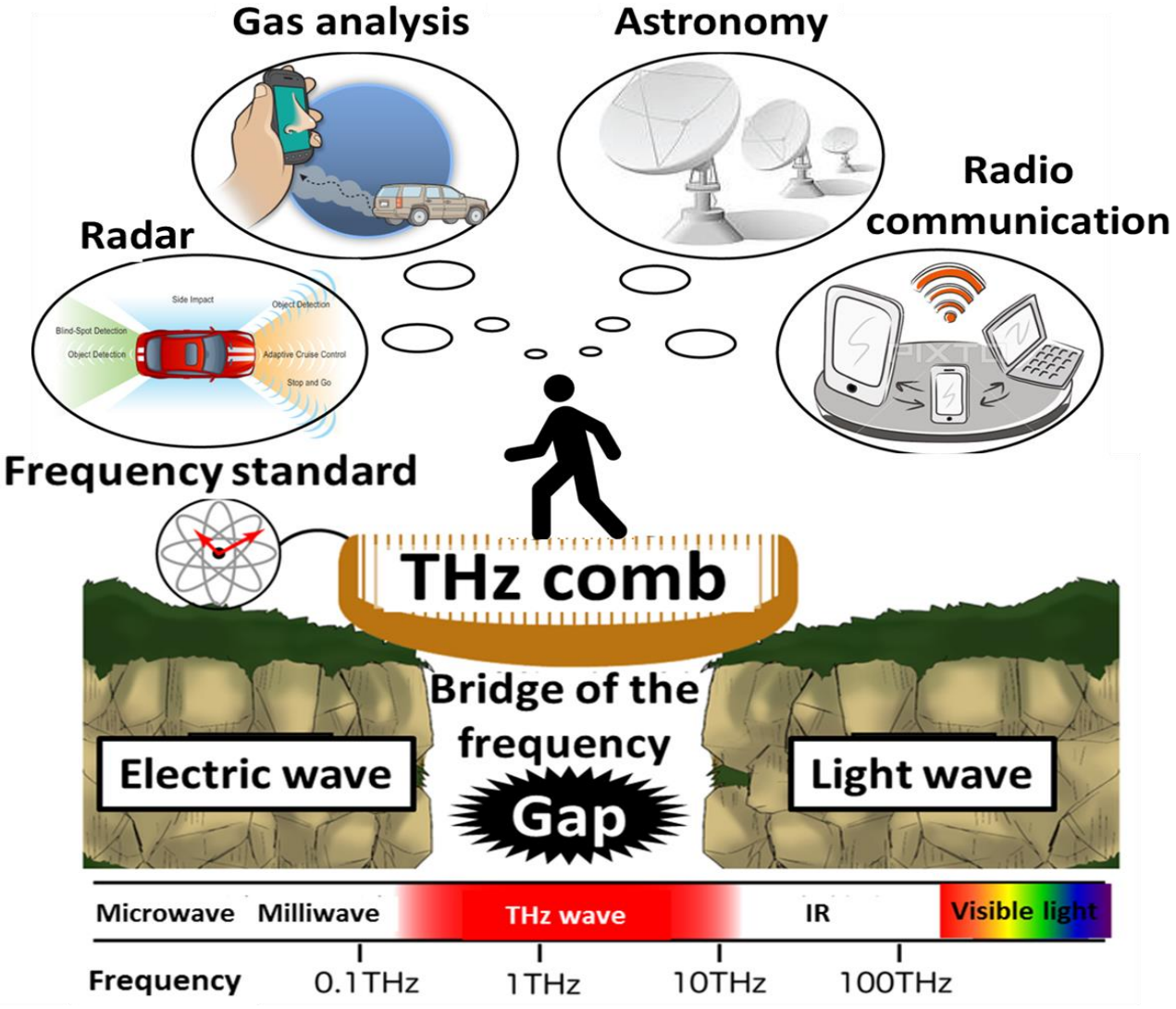
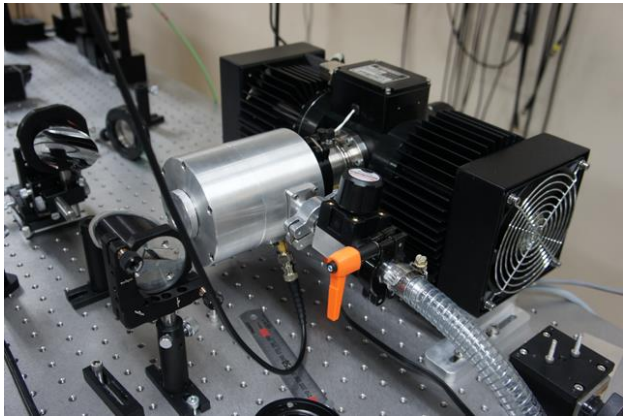
THz comb bridges THz gap as frequency scale



Frequency measurement of CW-THz wave

Practical CW-THz sources



THz-QCL

UTC-PD

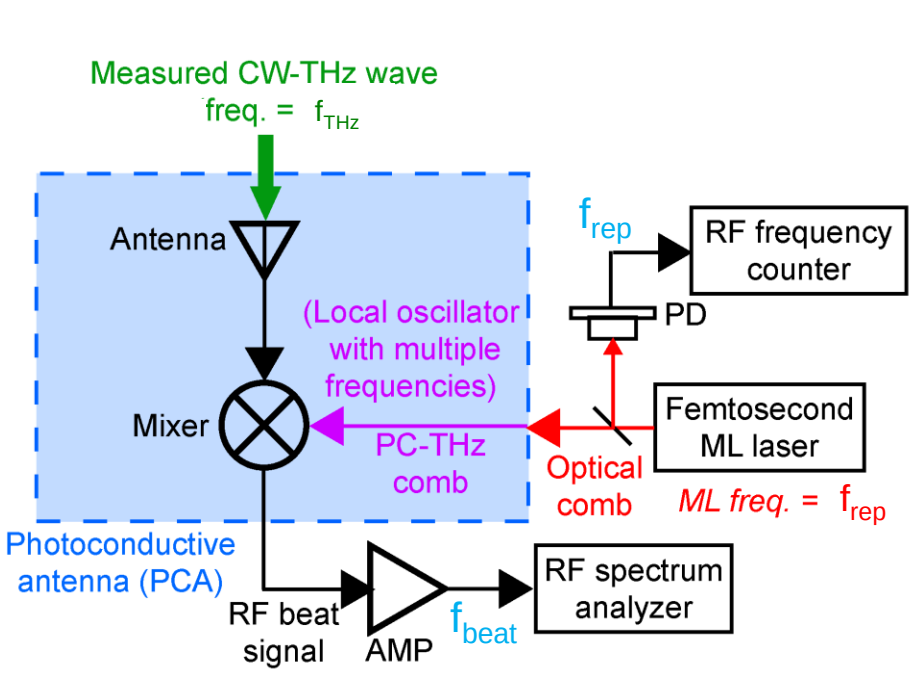
Conventional methods of the frequency measurement

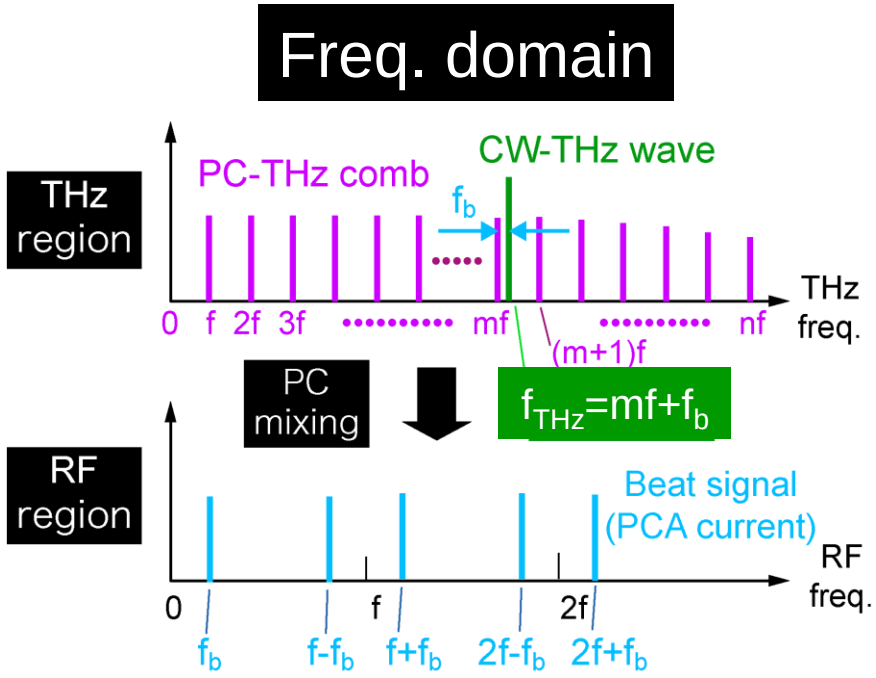
- Electrical heterodyne method
- Optical interferometric method

→ **Cryogenic cooling of mixers or detectors is required**

Frequency measurement of CW-THz wave without the need for cryogenic cooling is strongly required !

THz-comb-referenced frequency measurement



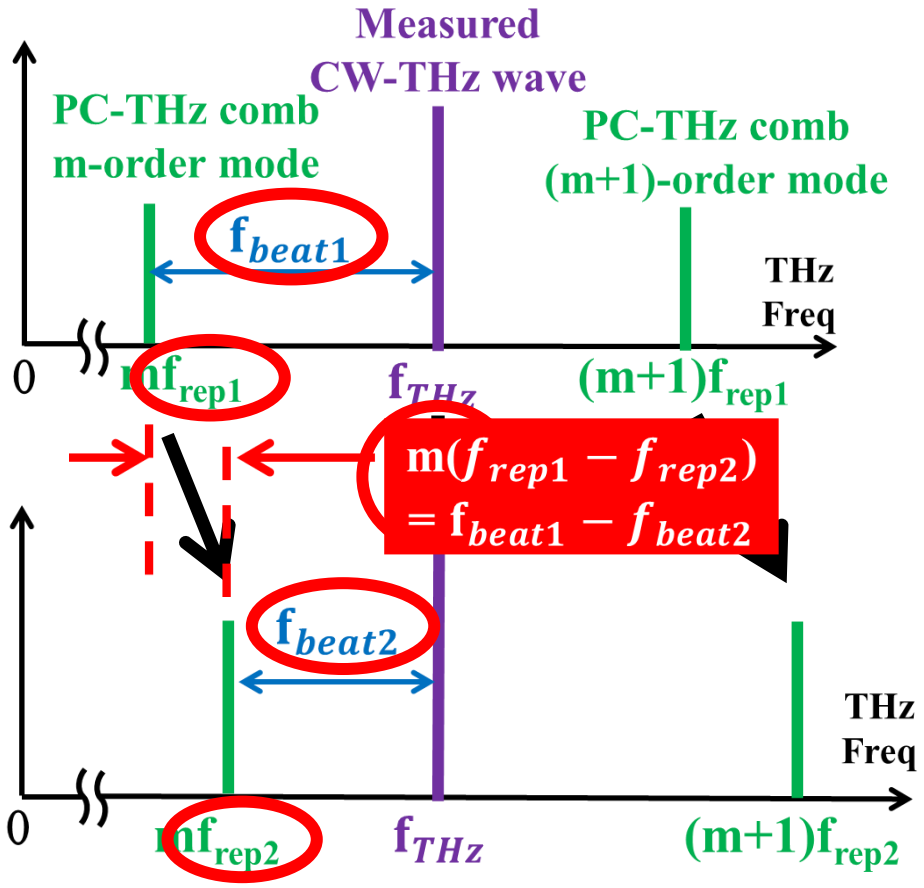


$$f_{THz} = m f_{rep} \pm f_{beat}$$

m: order of comb mode
f_{rep}: ML frequency
f_{beat}: beat frequency

*Ref) S. Yokoyama et al, Opt. Express **16**, 13052-13061 (2008).*
*T. Yasui et al. Opt. Express **17**, 17034-17043 (2009).*

Determination of m and sign of f_{beat}



Measurement of f_{rep1} and f_{beat1}

$$m = \frac{\left| f_{beat1} - f_{beat2} \right|}{\left| f_{rep1} - f_{rep2} \right|}$$

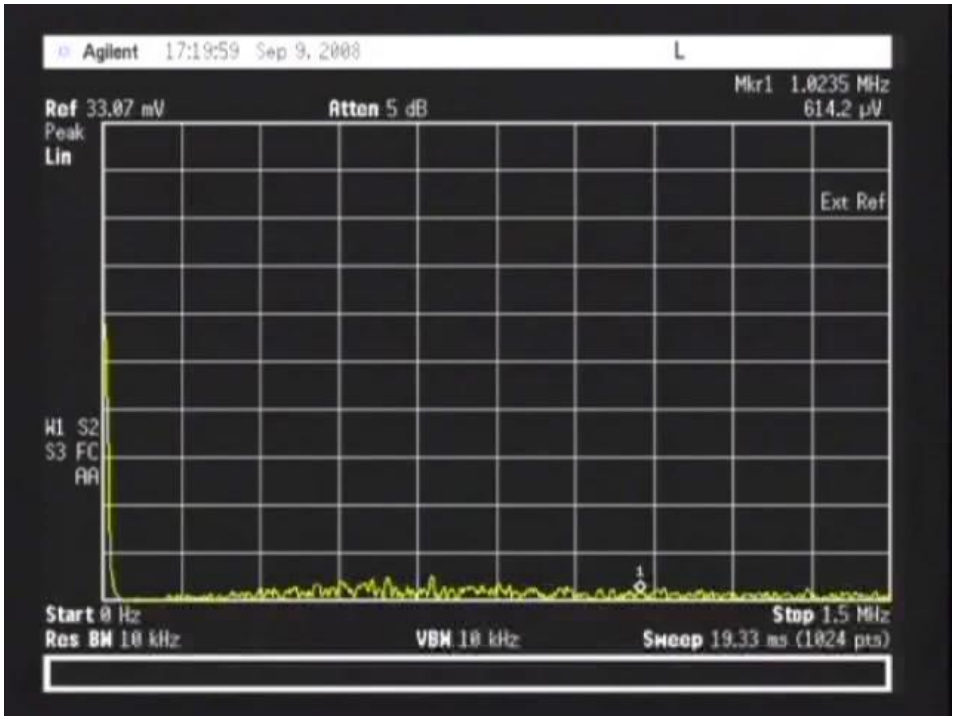
Measurement of f_{rep2} and f_{beat2}

Assumption : f_{THz} is sufficiently stable during measurements of f_{beat1} and f_{beat2}

For example

CW-THz source (UTC-PD)

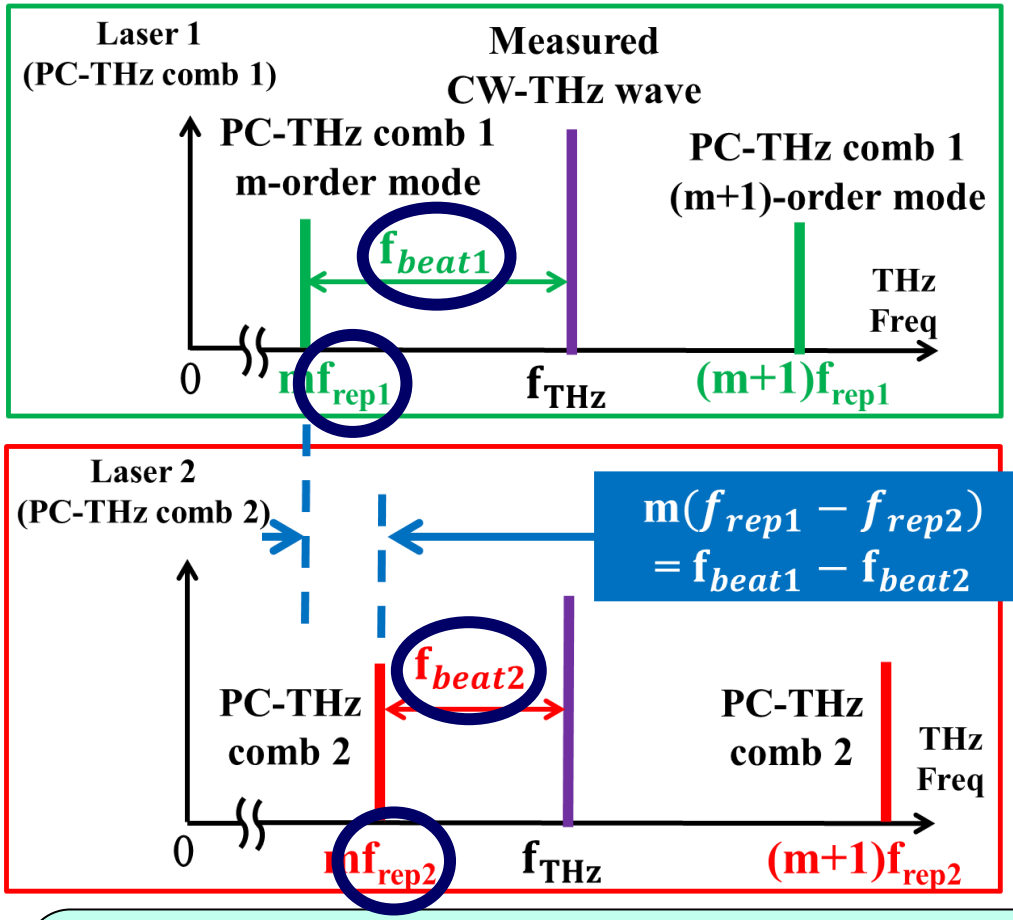
- fast frequency fluctuation
- large frequency fluctuation (mode hopping)



Present talk

Real-time determination of the fast or largely fluctuating CW-THz frequency using dual PC-THz combs .

Real-time determination of CW-THz frequency



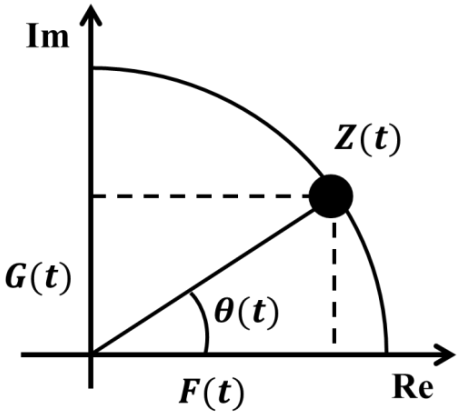
parallel measurement using dual PC-THz combs !

$$m = \frac{\left| f_{beat1} - f_{beat2} \right|}{\left| f_{rep1} - f_{rep2} \right|}$$

$$f_{THz} = mf_{rep1} - f_{beat1} \qquad [(f_{beat1} - f_{beat2})/(f_{rep1} - f_{rep2}) > 0]$$

$$f_{THz} = mf_{rep1} + f_{beat1} \qquad [(f_{beat1} - f_{beat2})/(f_{rep1} - f_{rep2}) < 0]$$

Instantaneous frequency measurement using Hilbert transformation



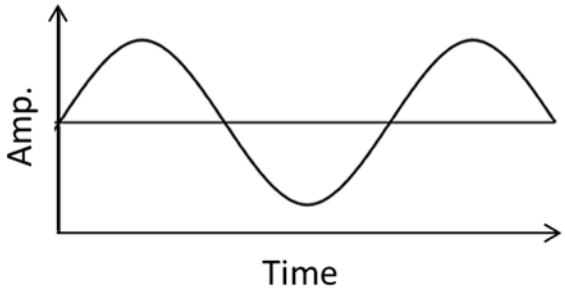
Ref) H. Füser et al, Appl. Phys. Lett. ***99****, 121111 (2011).*

$$Z(t) = F(t) + iG(t)$$

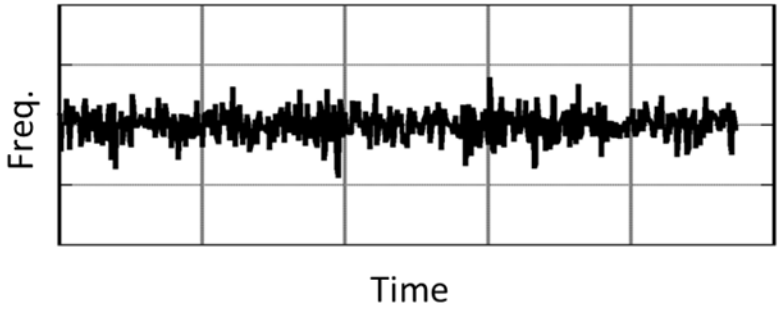
***Z(t)*: analytic signal** $F(t)$: **measurement signal** $G(t)$: **signal after Hilbert transform**

$$\theta(t) = \arg[Z(t)] = \tan^{-1}\left[\frac{G(t)}{F(t)}\right]$$

$$f = \frac{1}{2\pi} \times \frac{d\theta(t)}{dt}$$



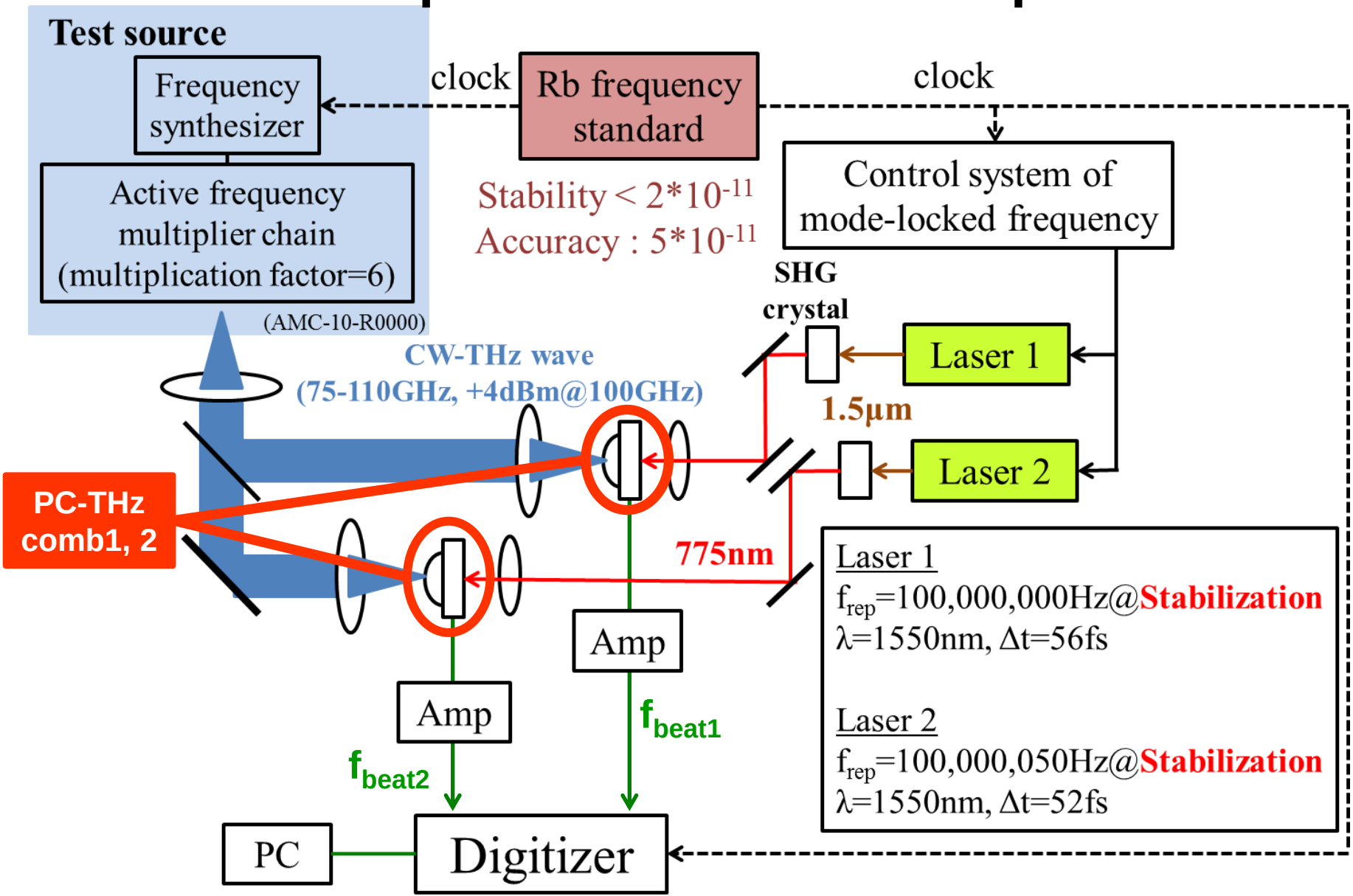
Hilbert transform



Temporal waveform of f_{beat}

Instantaneous frequency of f_{beat}

Experimental setup

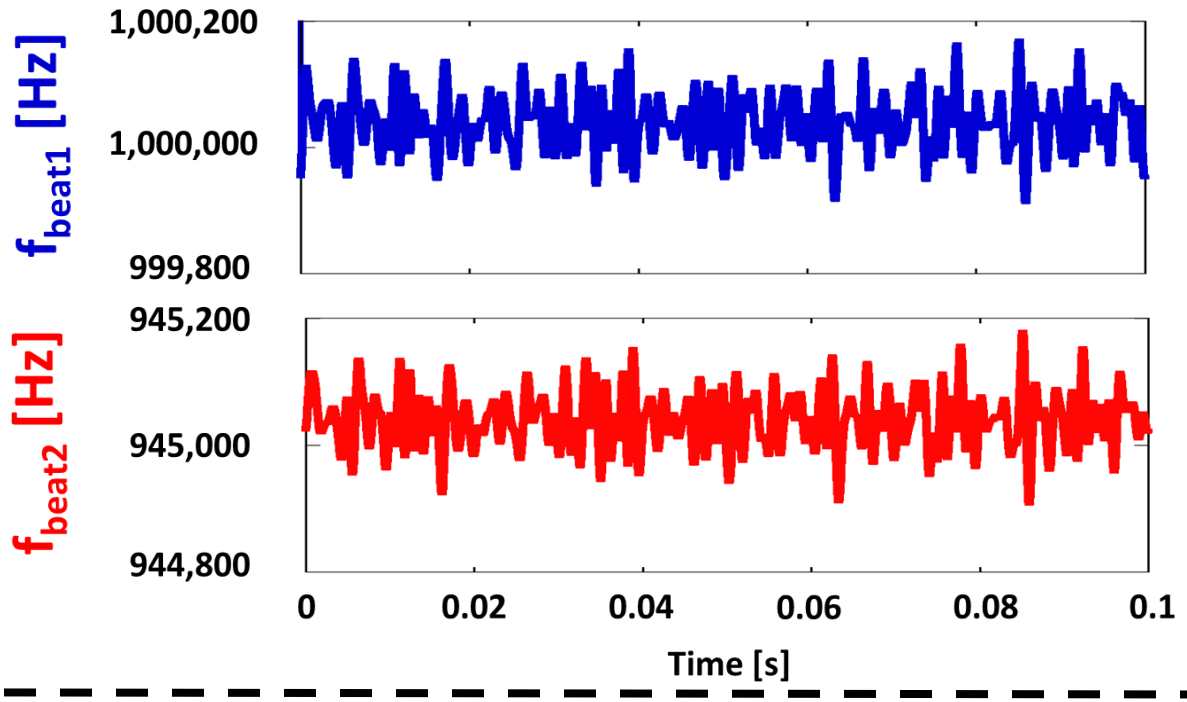


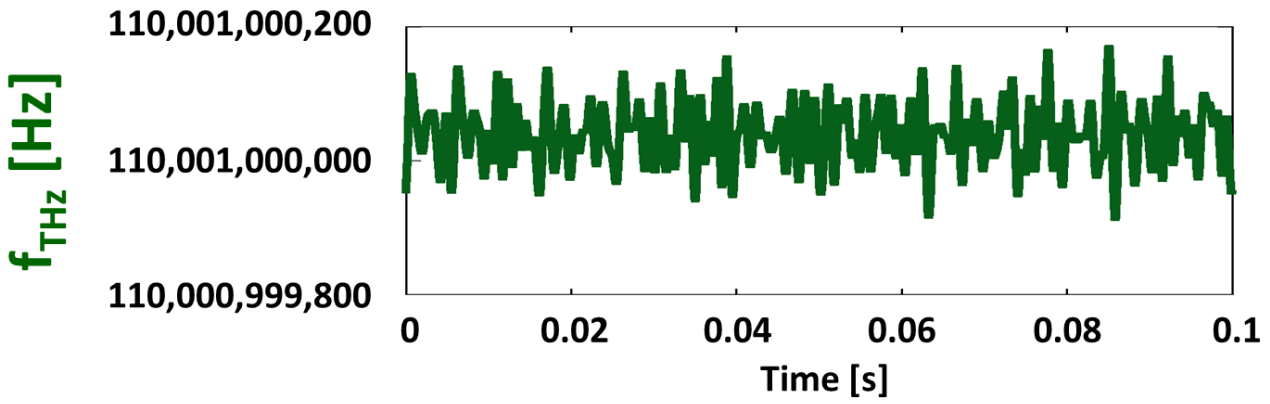
Real-time determination of f_{THz}

Sampling rate 10MHz

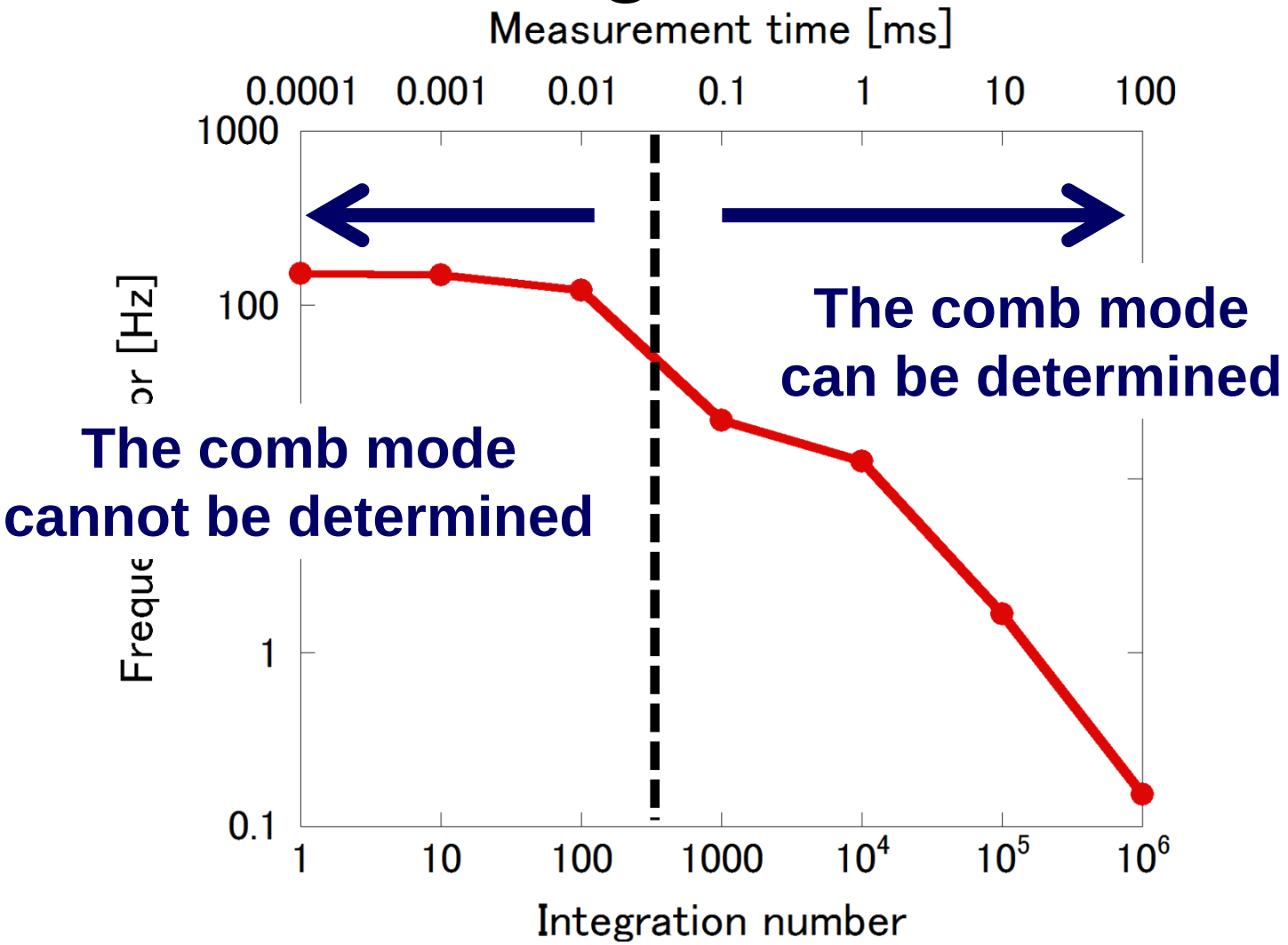
f_{rep1} = 100,000,000 Hz
f_{rep2} = 100,000,050 Hz

fixed

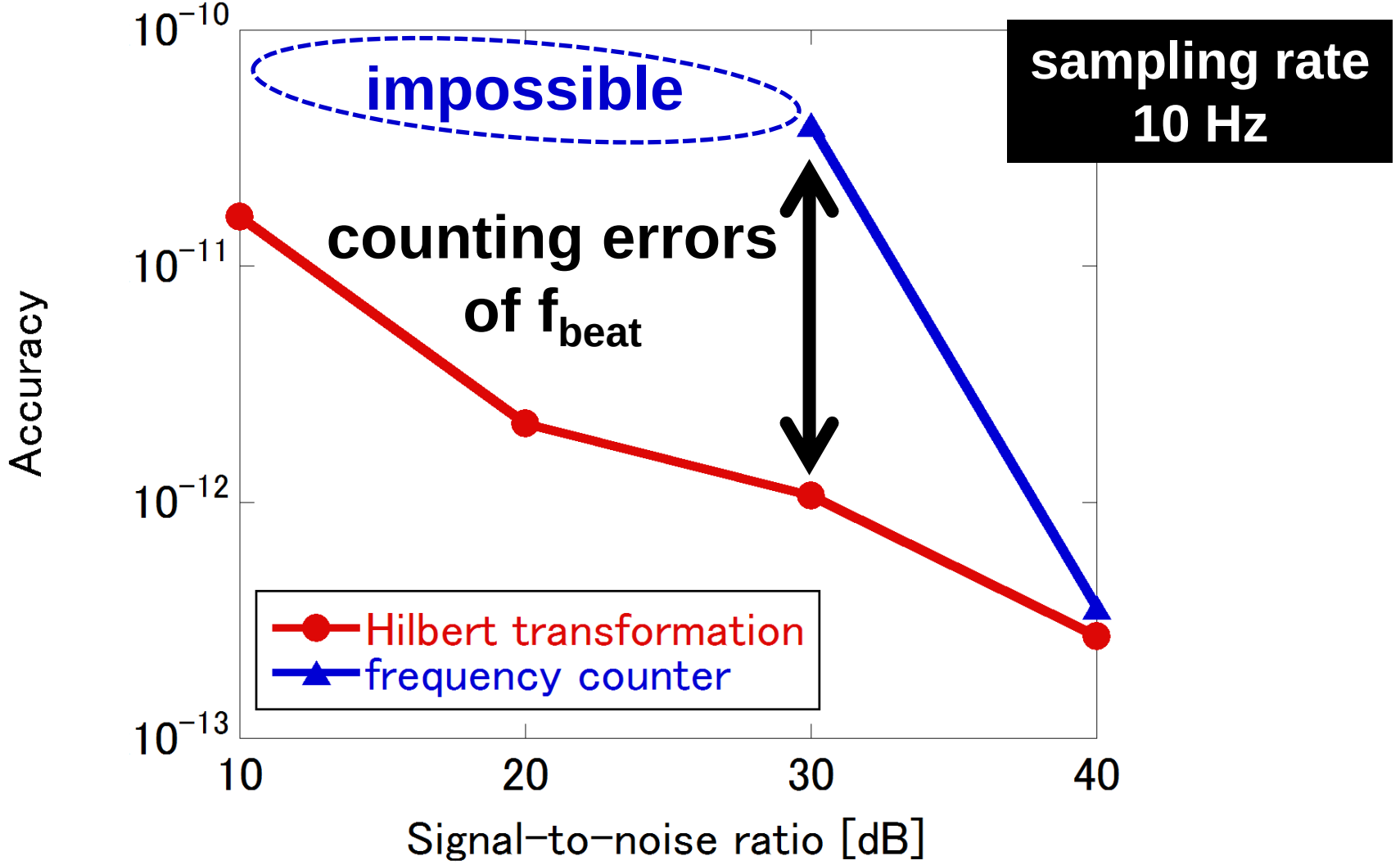




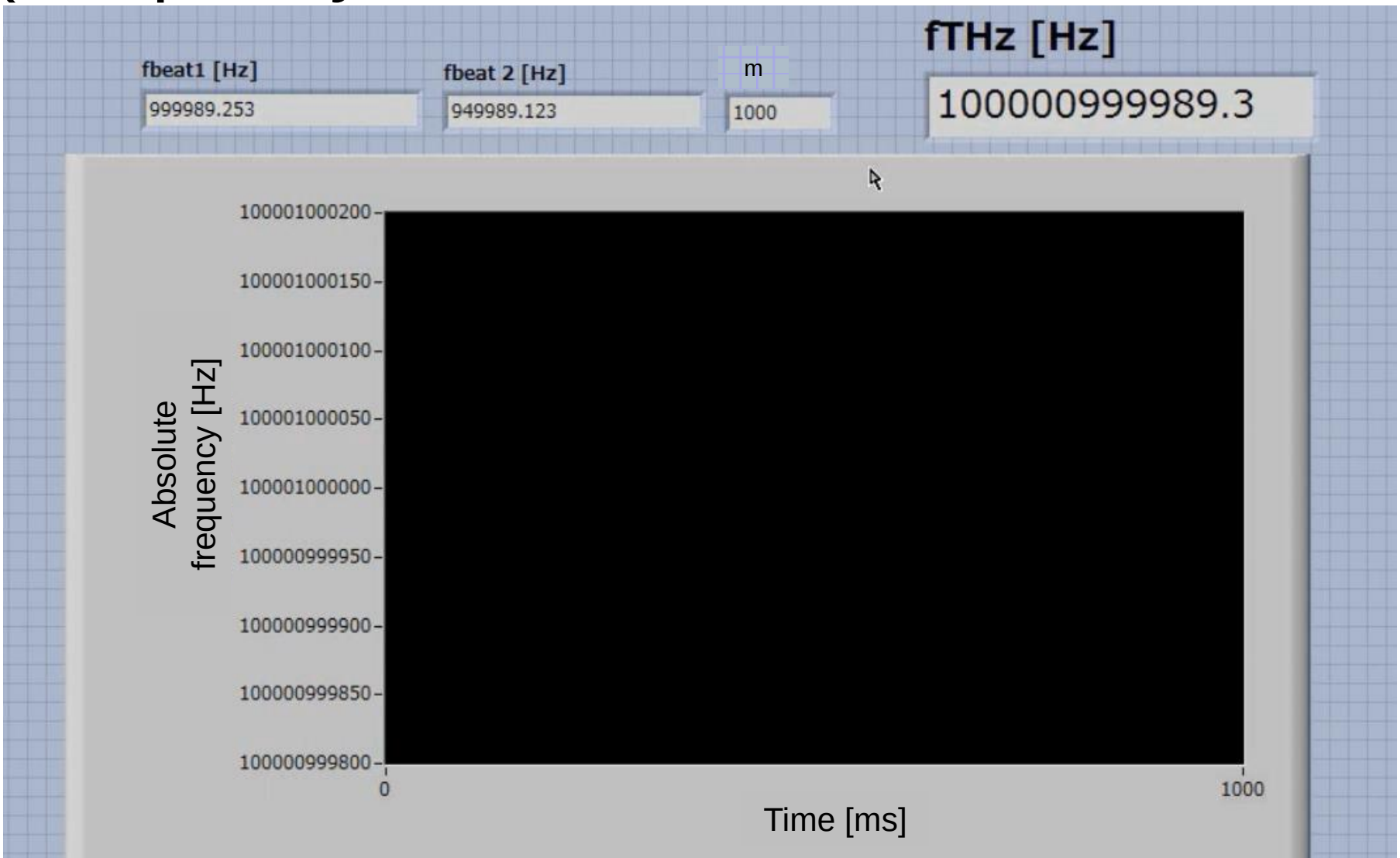
Frequency error with respect to a various integration number



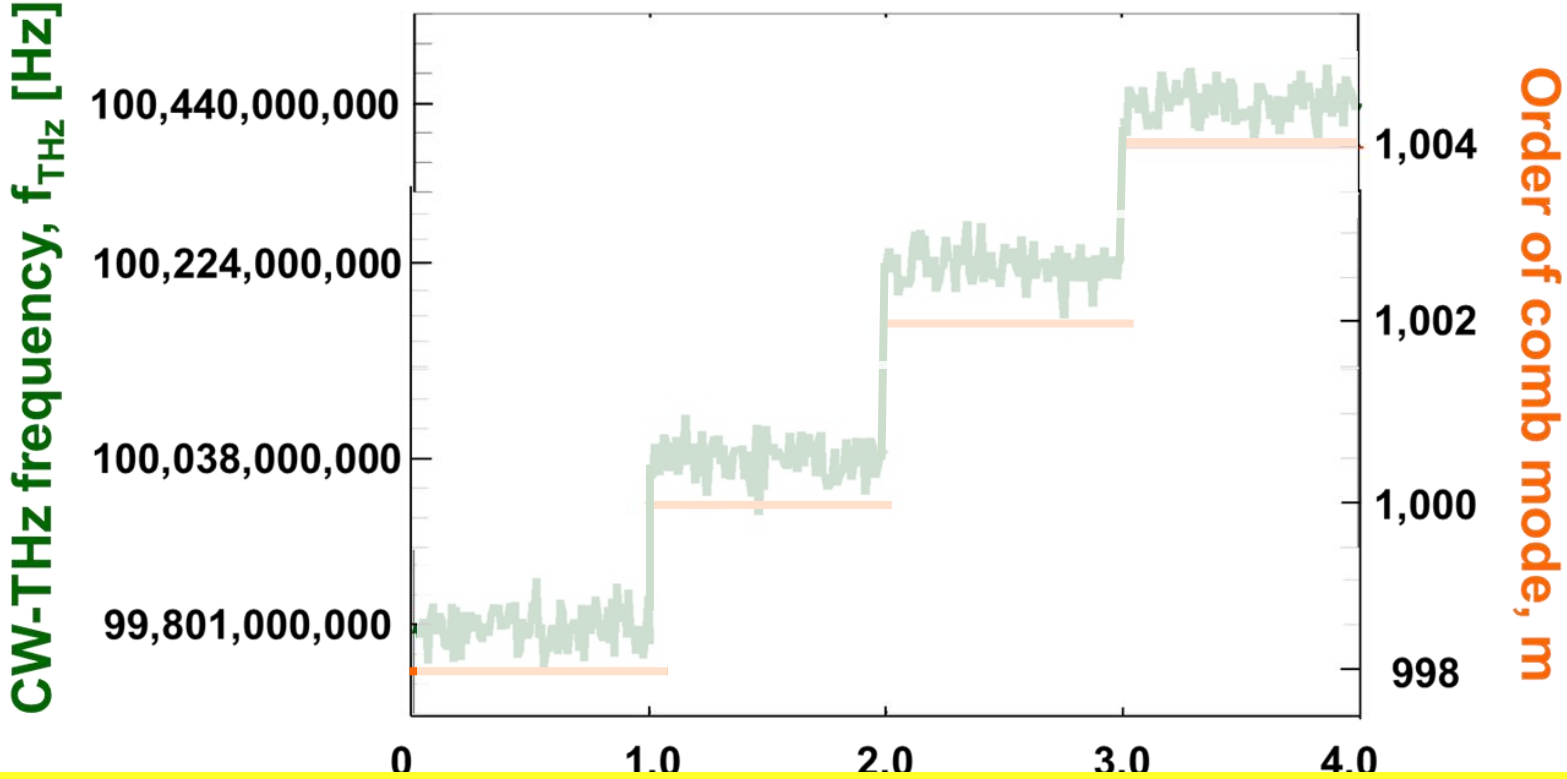
Comparison of accuracy between Hilbert transformation and frequency counter



Real-time monitoring of CW-THz wave ①
(Frequency fluctuation = 0.1 THz ±100 Hz)



Real-time monitoring of CW-THz wave ②
(Frequency fluctuation = 0.1THz + 200MHz)



A high potential for real time monitoring of large fluctuation such as mode hopping in CW-THz sources!

Summary

Real-time absolute frequency measurement of the fast or largely fluctuating CW-THz wave using dual PC-THz combs

(1) Frequency accuracy

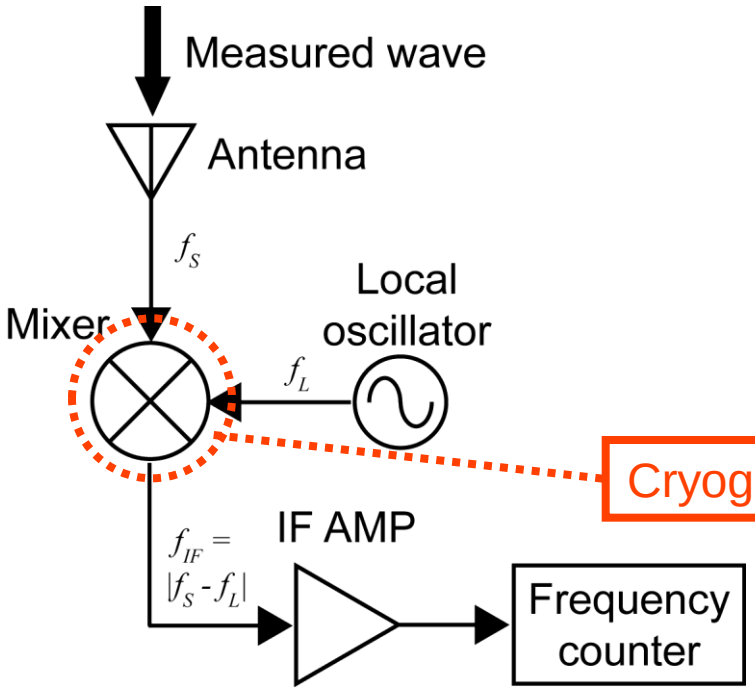
- 2.2×10^{-10} at a sampling rate of 10 kHz
- 1.5×10^{-12} at a sampling rate of 10 Hz

(2) Possible to determine f_{THz} at lower SNR (~10)

(3) Available for large change of f_{THz} across the comb mode

Conventional method

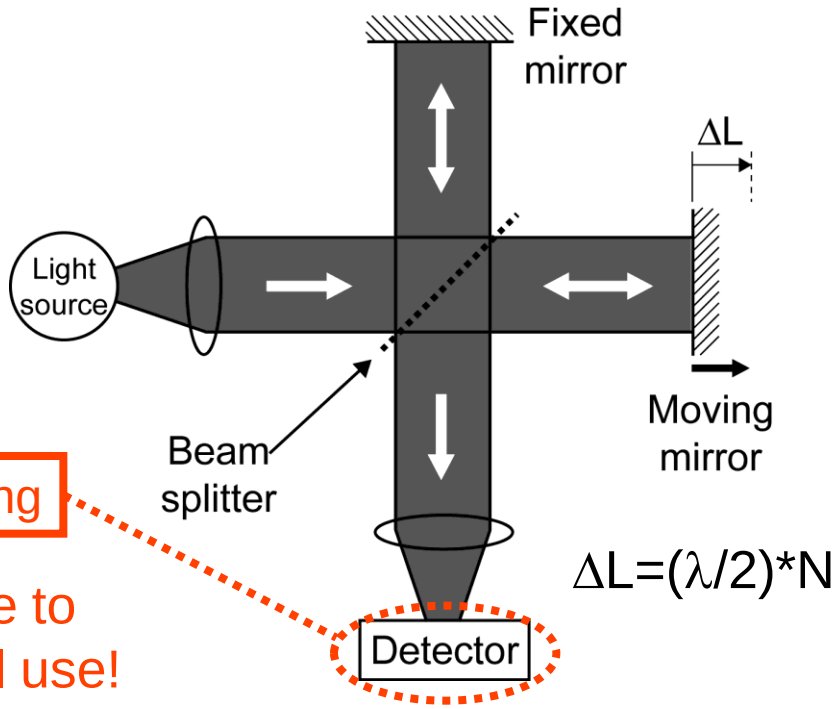
Electrical heterodyned method



Cryogenic cooling

Obstacle to practical use!

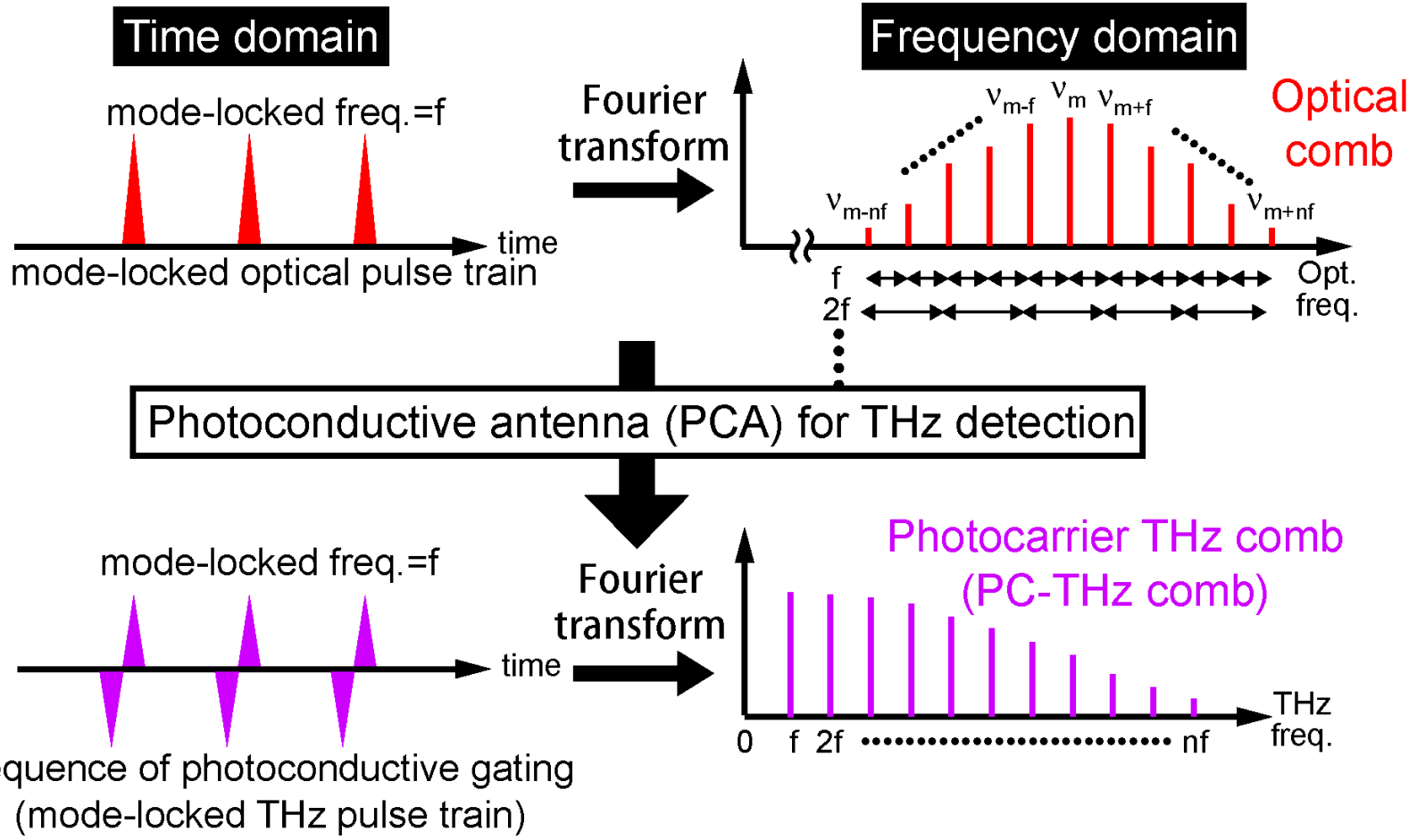
Optical interferometric method



Difficult to cover all frequency region of THz wave (0.1~10THz)

→Requirement of new method optimized for THz wave!

Optical comb and THz comb

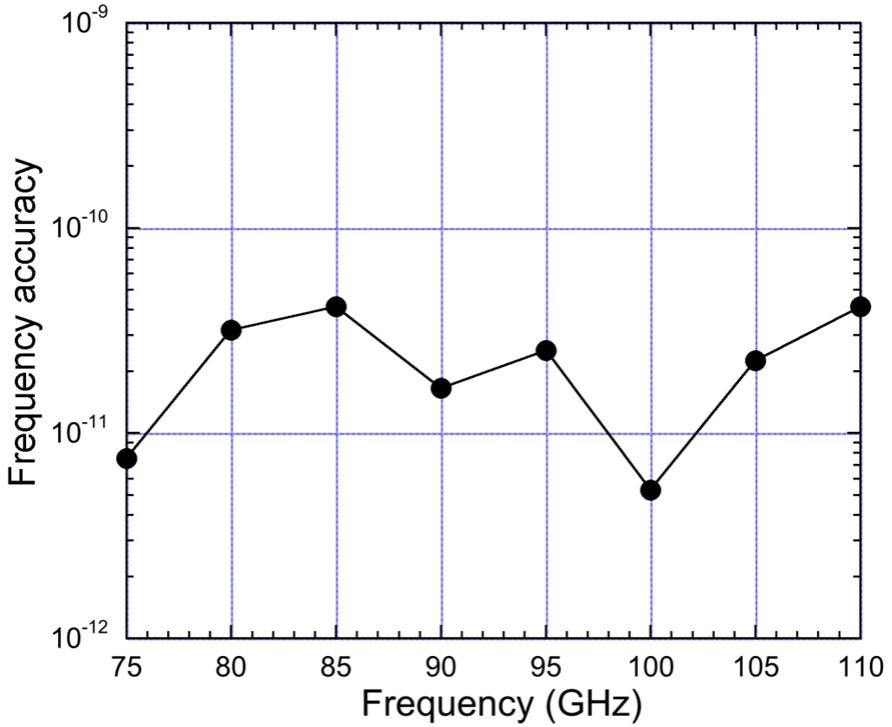


Simple, broadband selectivity, high spectral purity, offset free, and absolute frequency calibration

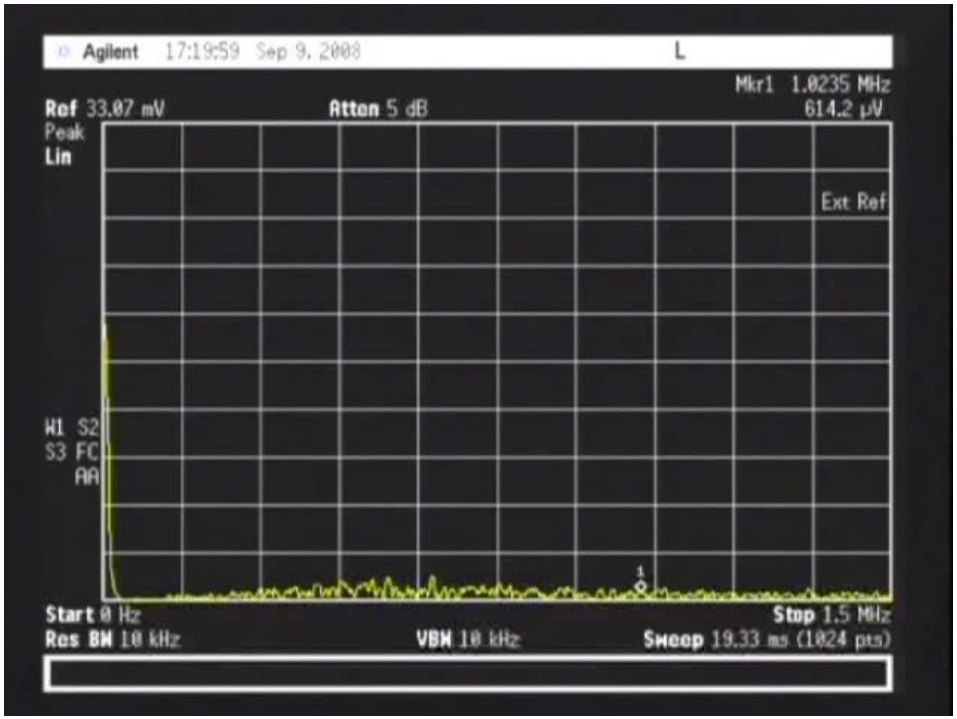
Previous study

*Ref) T. Yasui et al. Opt. Express **17**, 17034-17043 (2009).*

Absolute frequency measurement



Real-time monitoring of CW-THz wave



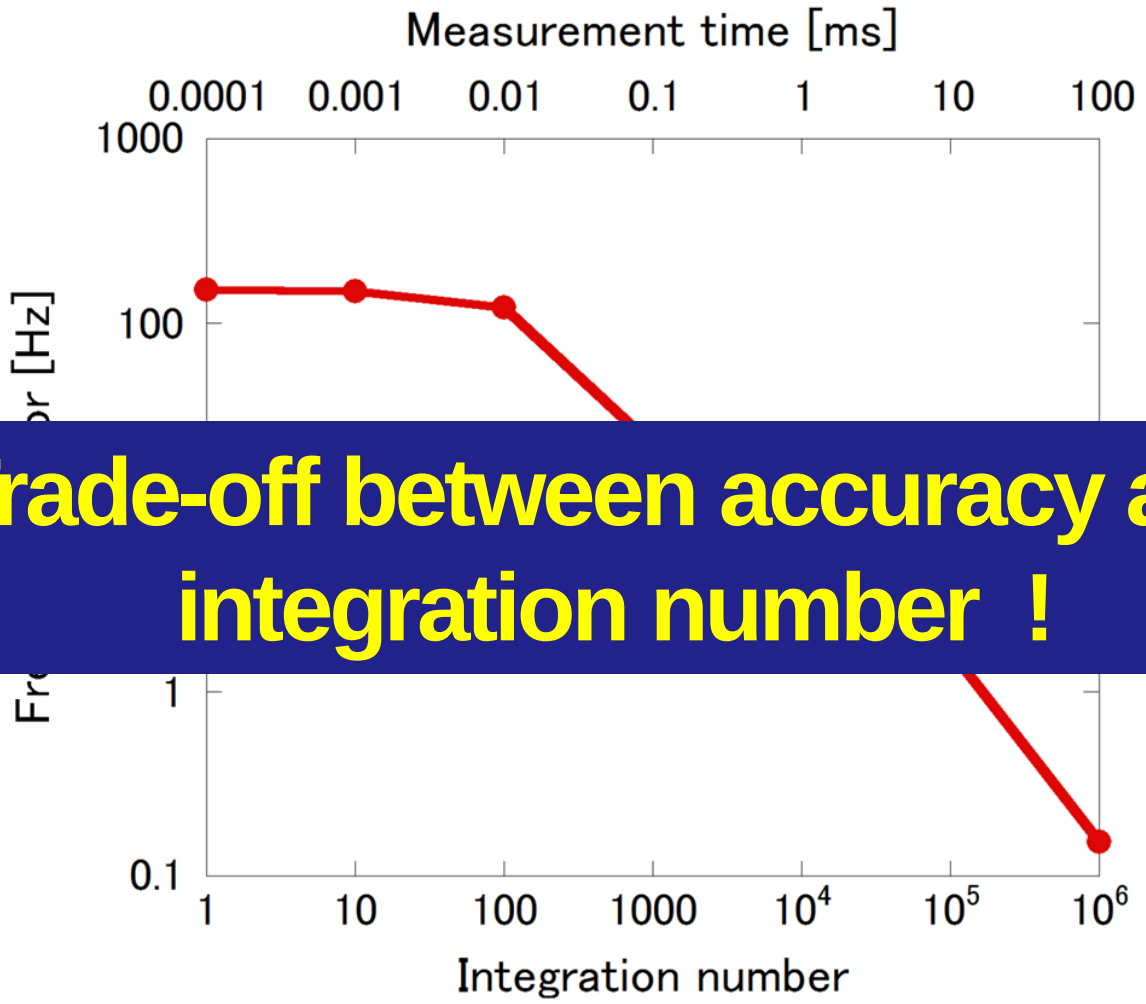
The advantage of Hilbert transformation

- Compared with frequency counter

1. The beat signal of lower SNR (~10) can be measured
2. Fast phenomenon can be measured

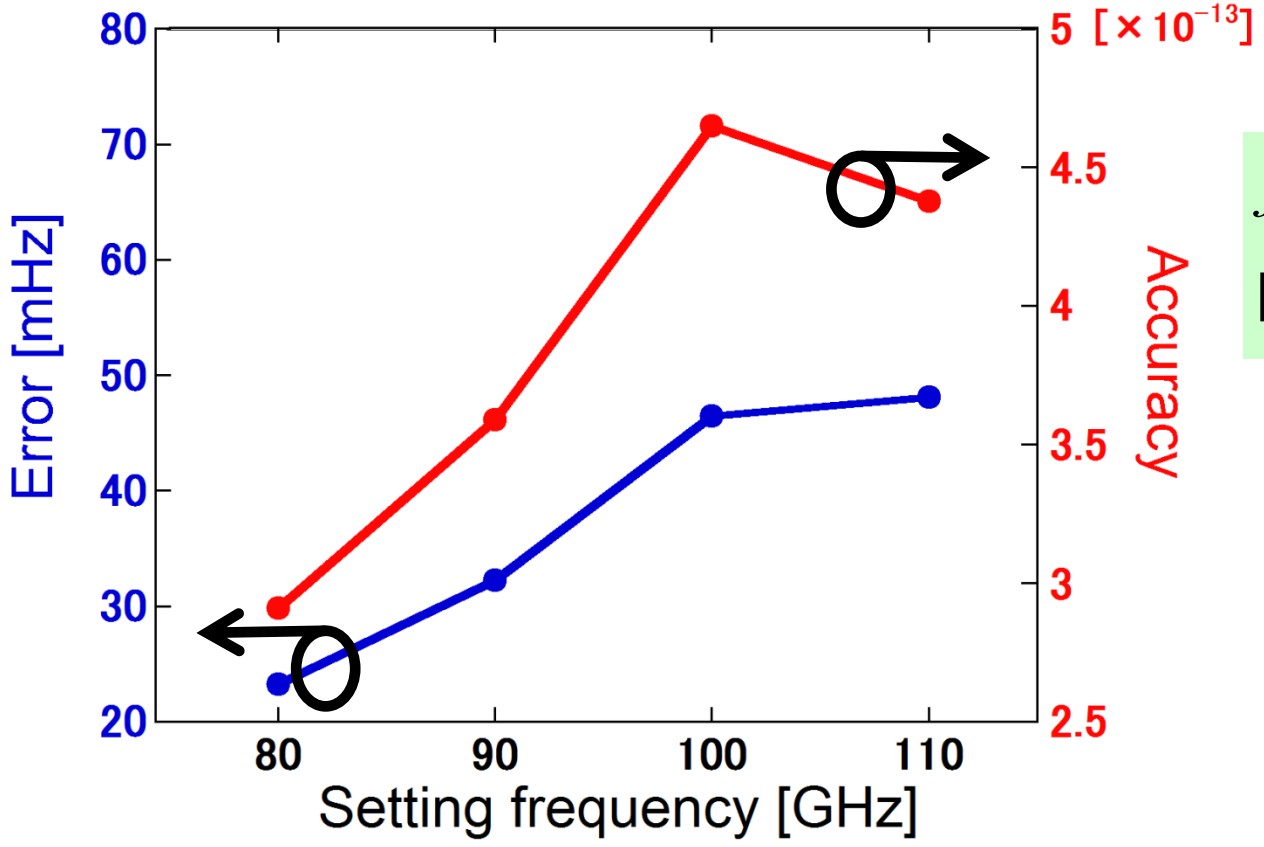
→frequency counter is limited by gate time

The disadvantage of Hilbert transformation



Trade-off between accuracy and integration number ！

Accuracy of absolute frequency measurement



Estimation of measurement error

$$f_{THz} = m f_{rep1} + f_{beat1}$$

$$\mathrm{D}f_{THz} = m\mathrm{D}f_{rep1} + \mathrm{D}f_{beat1}$$

Δf_{rep1} = 120μHz
Δf_{beat1} = 21mHz
m = 800~1100

↓

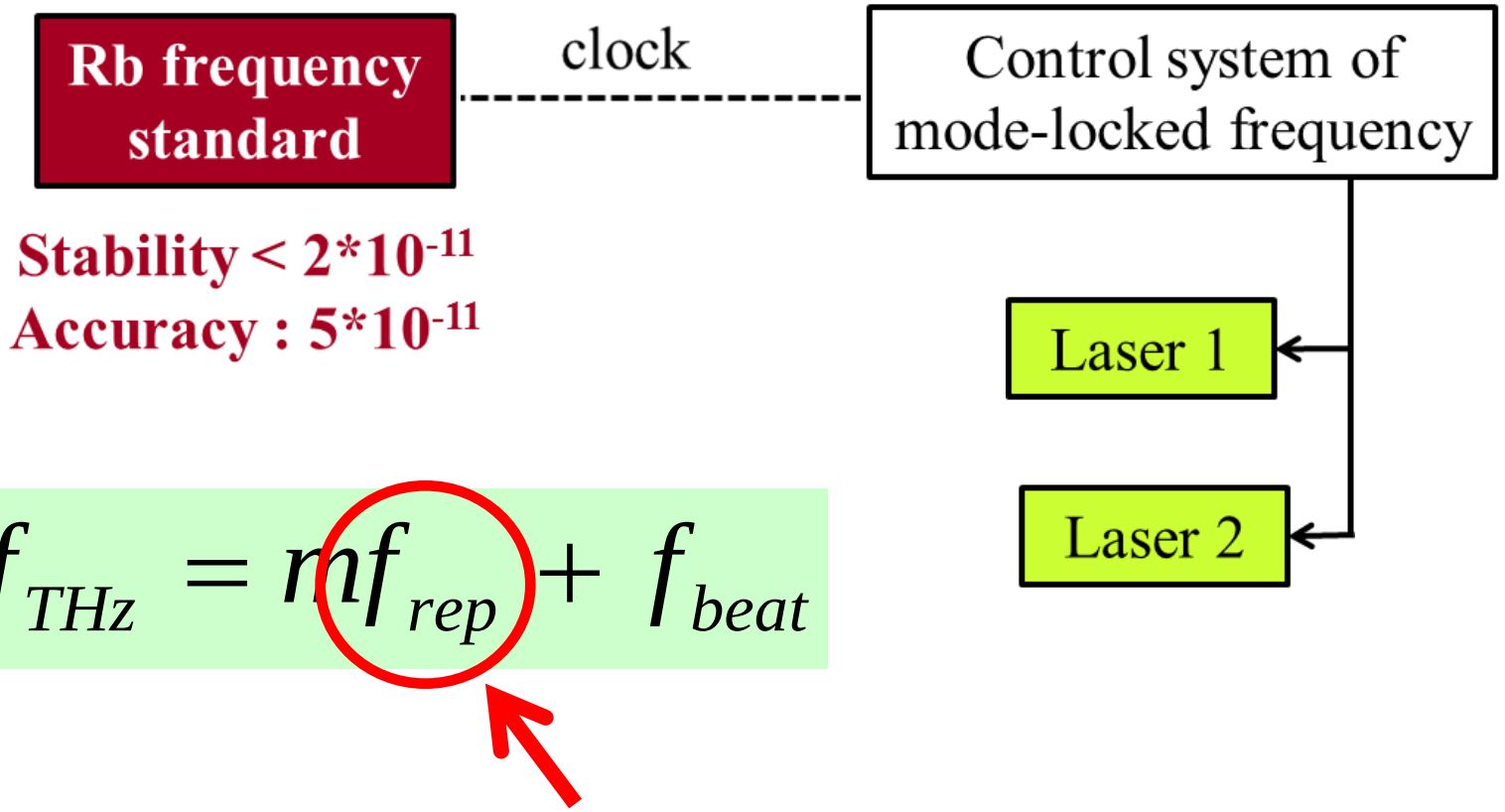
Δf_{THz} = 117~153mHz

Mean precision = $1.5*10^{-12}$

Accuracy

$$Accuracy = \frac{frequency\ error}{setting\ frequency}$$

The limitation of accuracy



$$f_{THz} = mf_{rep} + f_{beat}$$

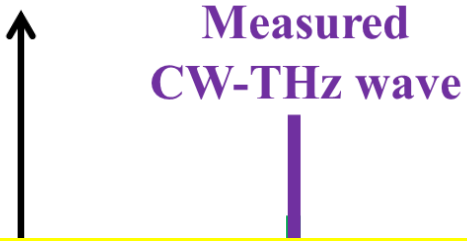
The accuracy is limited by stability of f_{rep}

The fast or largely fluctuation of CW-THz wave

limited by response speed or sensitivity of PCA detector

However

- mf_{rep} and f_{THz} are same value → $f_{beat} = 0$



The m and f_{THz} cannot be determine due to no beat signal !!

Real-time absolute frequency measurement using a single PC-THz comb

1. modulating f_{rep}

→Δf_{rep} and Δf_{beat} can be measured

2. using free-running laser

→Δf_{rep} and Δf_{beat} can be measured

The m and f_{THz} can be determined by measuring Δf_{rep} and Δf_{beat} at the same time !!