We10-4

Real-time frequency measurement of CW-THz wave based on dual THz combs

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Background

Frequency is a fundamental physical quantity of electromagnetic wave

THz frequency metrology is required for various THz applications

Advent of practical CW-THz sources (THz-QCL, RTD, photomixing sources)

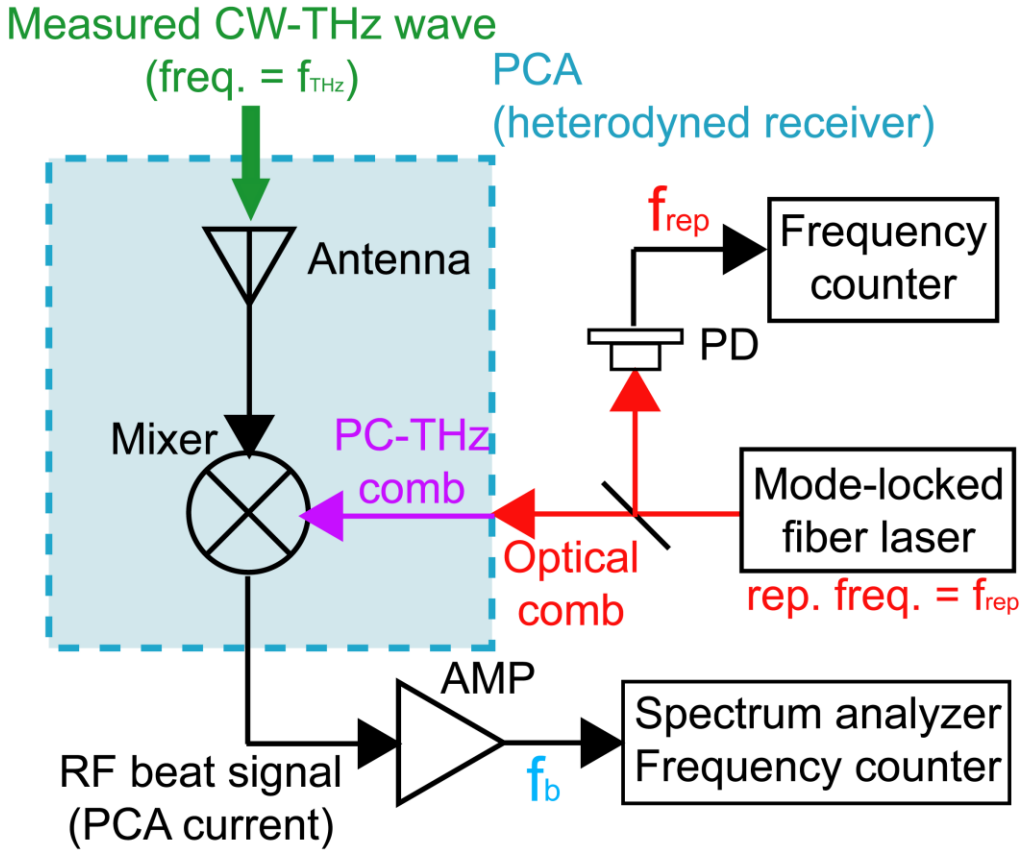
Precise frequency measurement of CW-THz wave is required!

However, techniques of absolute frequency measurement for CW-THz wave are still immature!

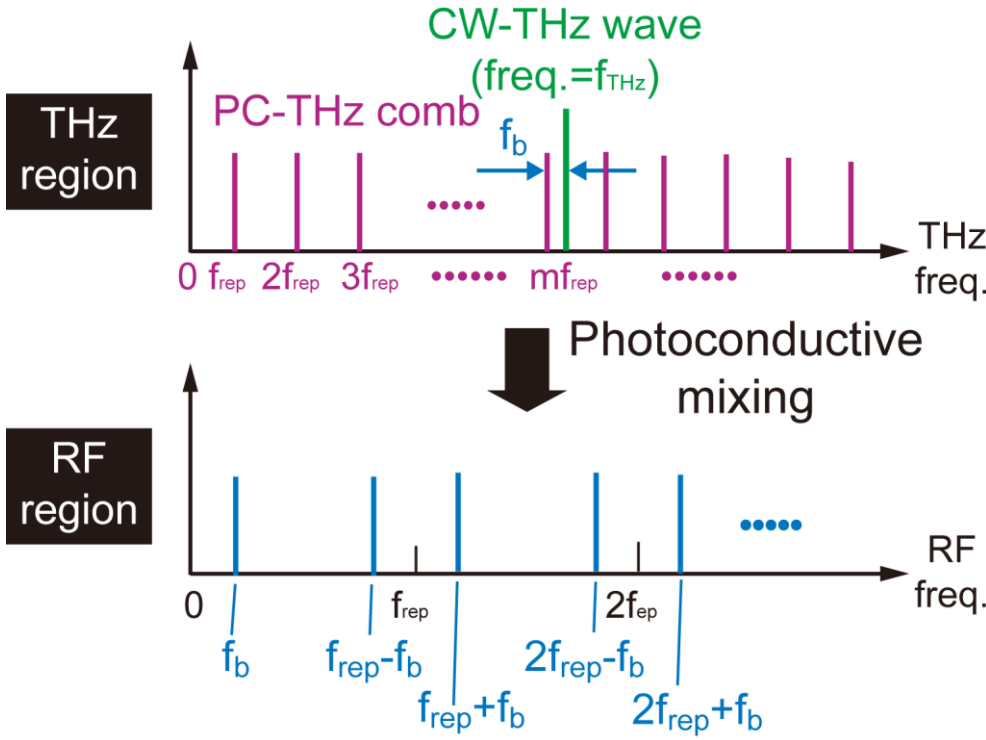
THz spectrum analyzer

OpEx **16**, 13052 (2008).
OpEx **17**, 17034 (2009).

Principle



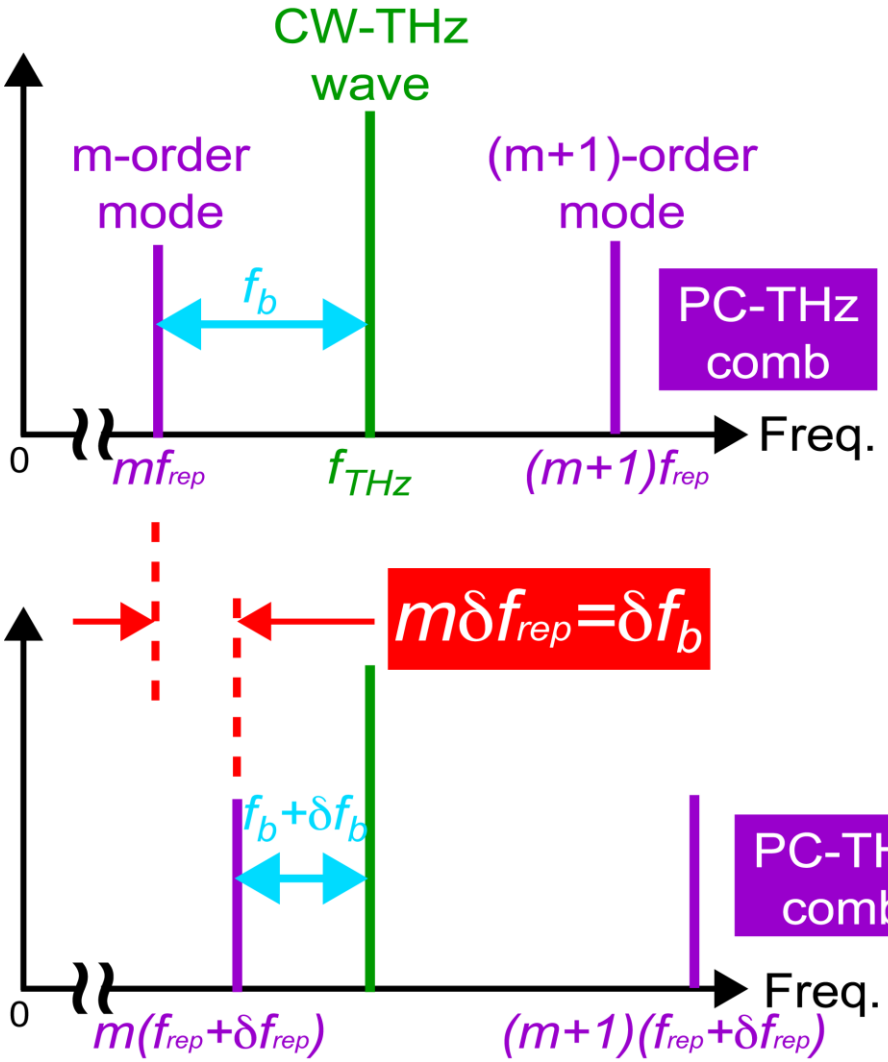
Freq. domain



$$f_{THz} = mf_{rep} \pm f_b$$

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

Limit for practical use (1)



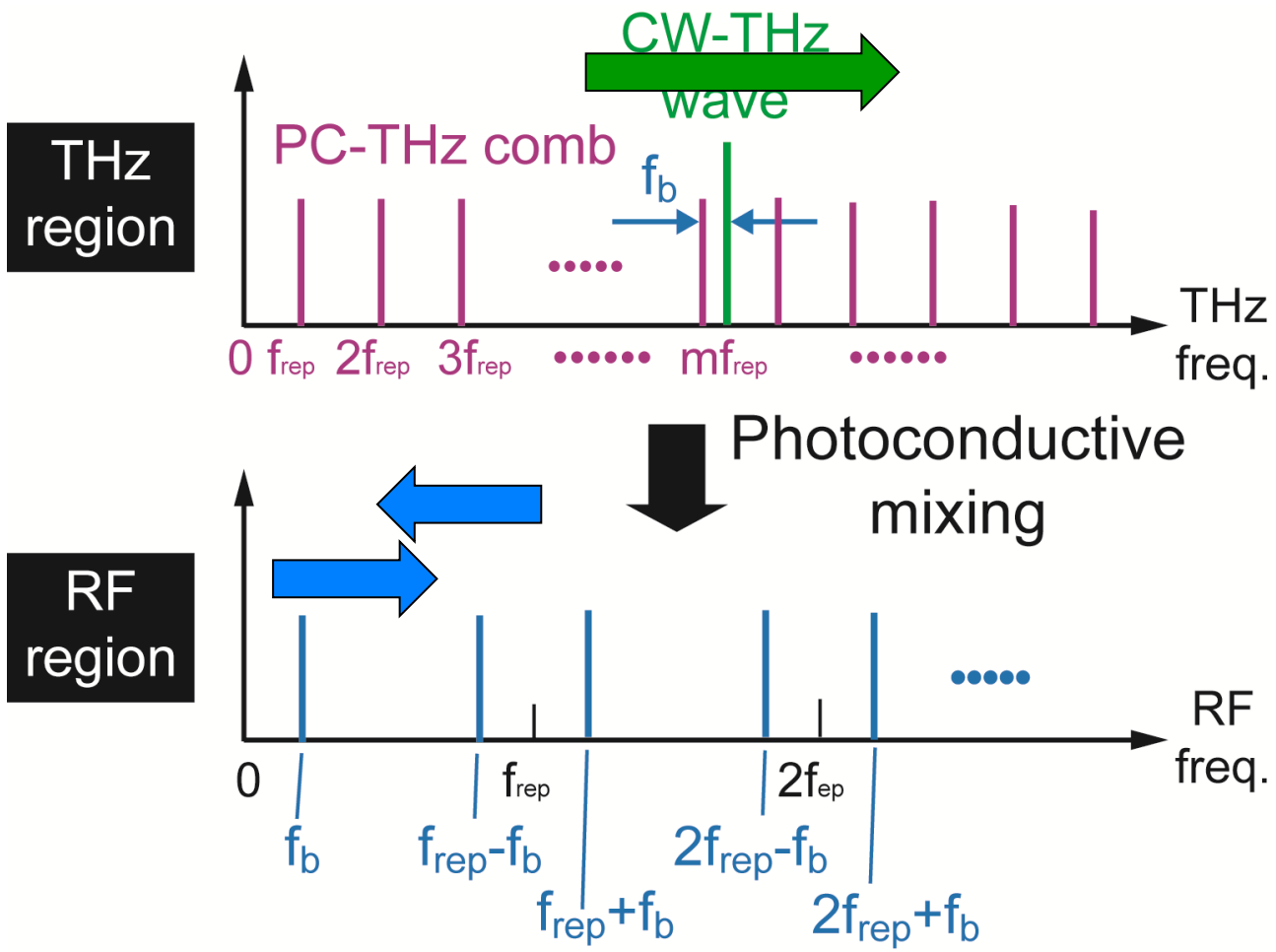
Shift of ML freq. f_{rep} by δf_{rep}
($f_{rep} \rightarrow f_{rep}+\delta f_{rep}$)

$$m = \frac{|df_b|}{|df_{rep}|}$$

Change of beat freq. f_b by δf_b
($f_b \rightarrow f_b+\delta f_b$)

Two-step measurement of f_{rep} and f_b

Limit for practical use (2)



$f_{THz} = mf_{rep}$

☞ $f_b = 0$

$f_{THz} = (m+1/2)f_{rep}$

☞ $f_b = f_{rep}-f_b$

f_b can not be determined correctly

Tuning range of CW-THz wave is limited by a half of frequency interval in PC-THz comb

Problems of previous studies for practical use

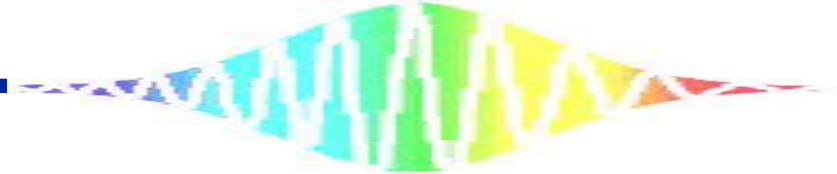
(1) **Not real-time determination**

(2) **Limitation for tuning range**

Present talk

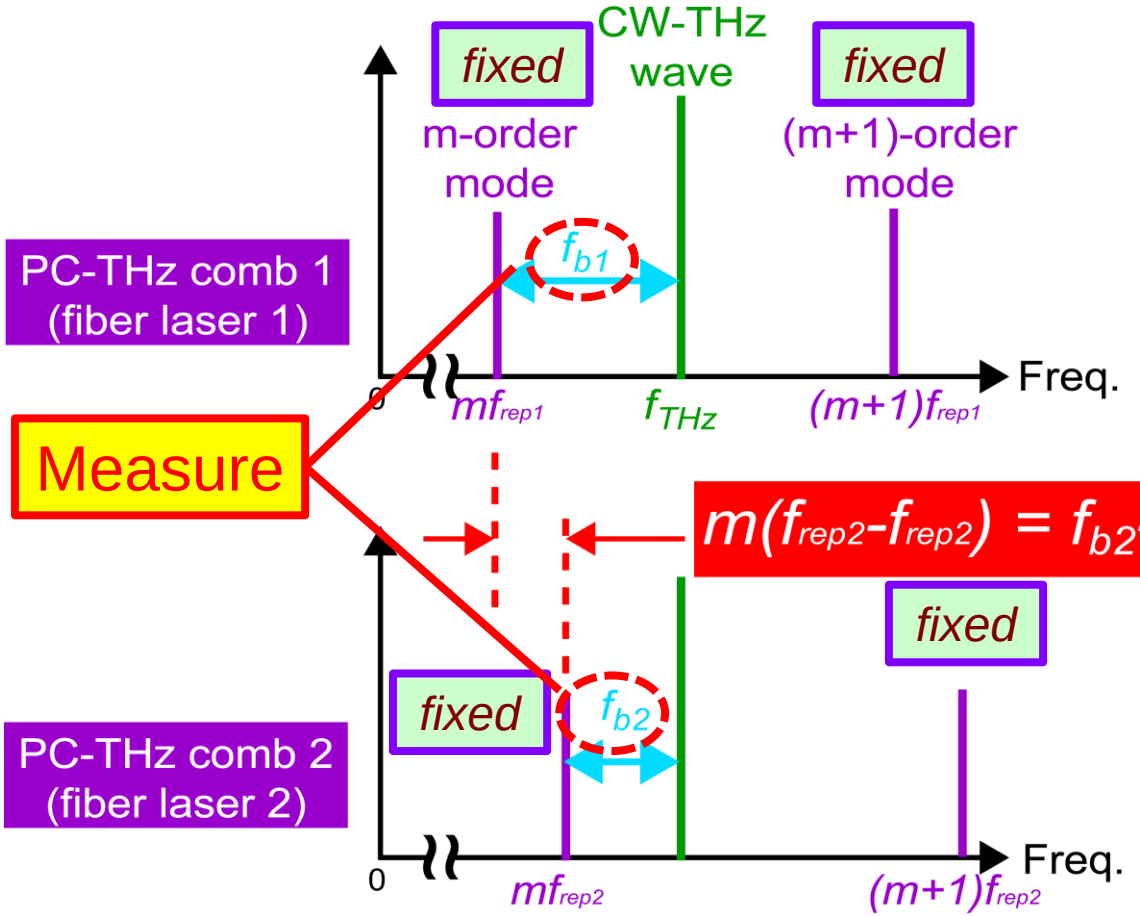
(1) **Real-time determination** of CW-THz wave using dual PC-THz combs

(2) **Real-time monitoring** of CW-THz wave sweeping over frequency interval of PC-THz comb



(1) Real-time determination of fixed CW-THz wave using dual PC-THz combs

Use of dual PC-THz combs



Real-time determination

$$m = \frac{|f_{b2} - f_{b1}|}{|f_{rep2} - f_{rep1}|}$$

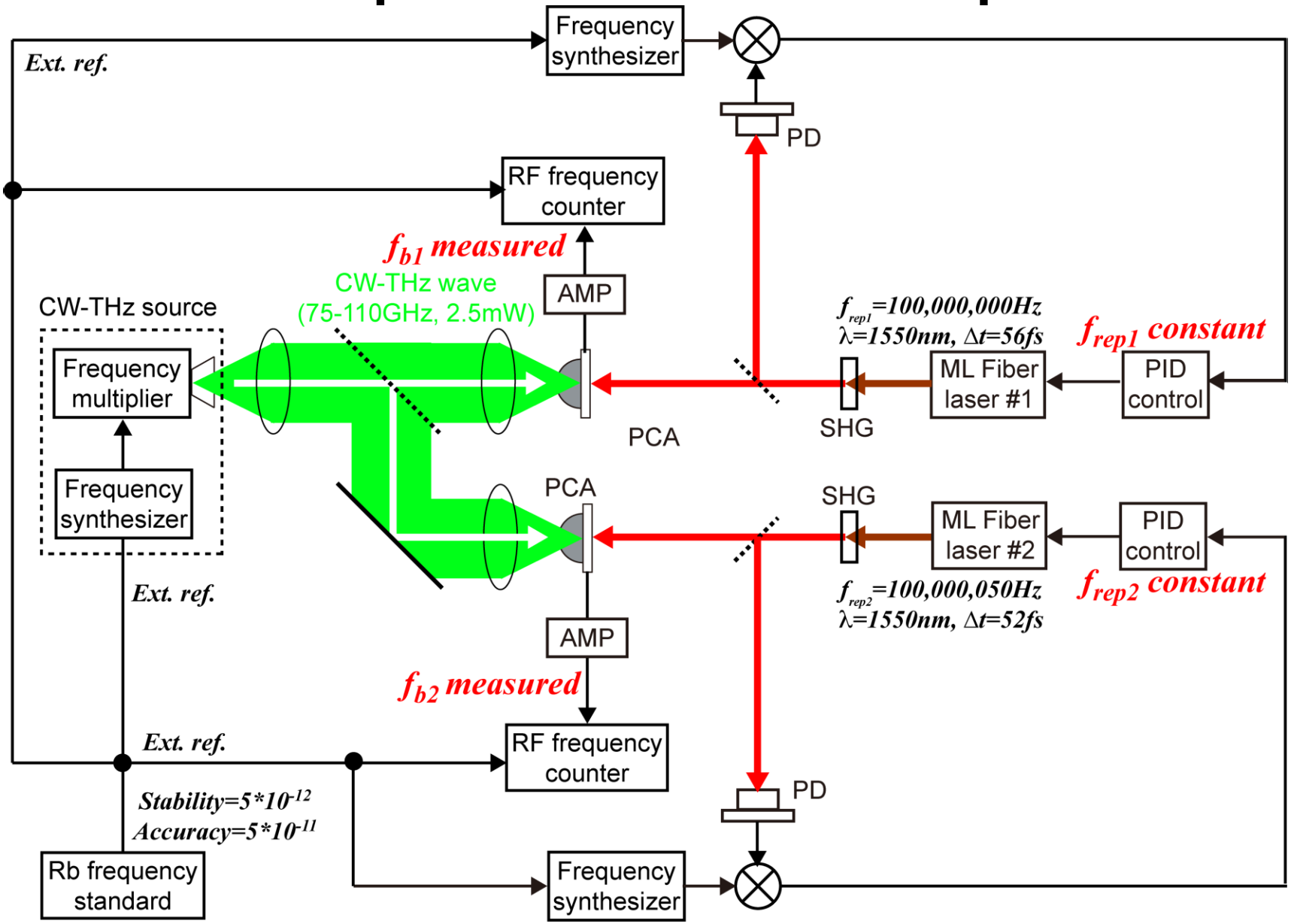
f_{rep1}, f_{rep2}: fixed at known values

f_{b1}, f_{b2}: measured

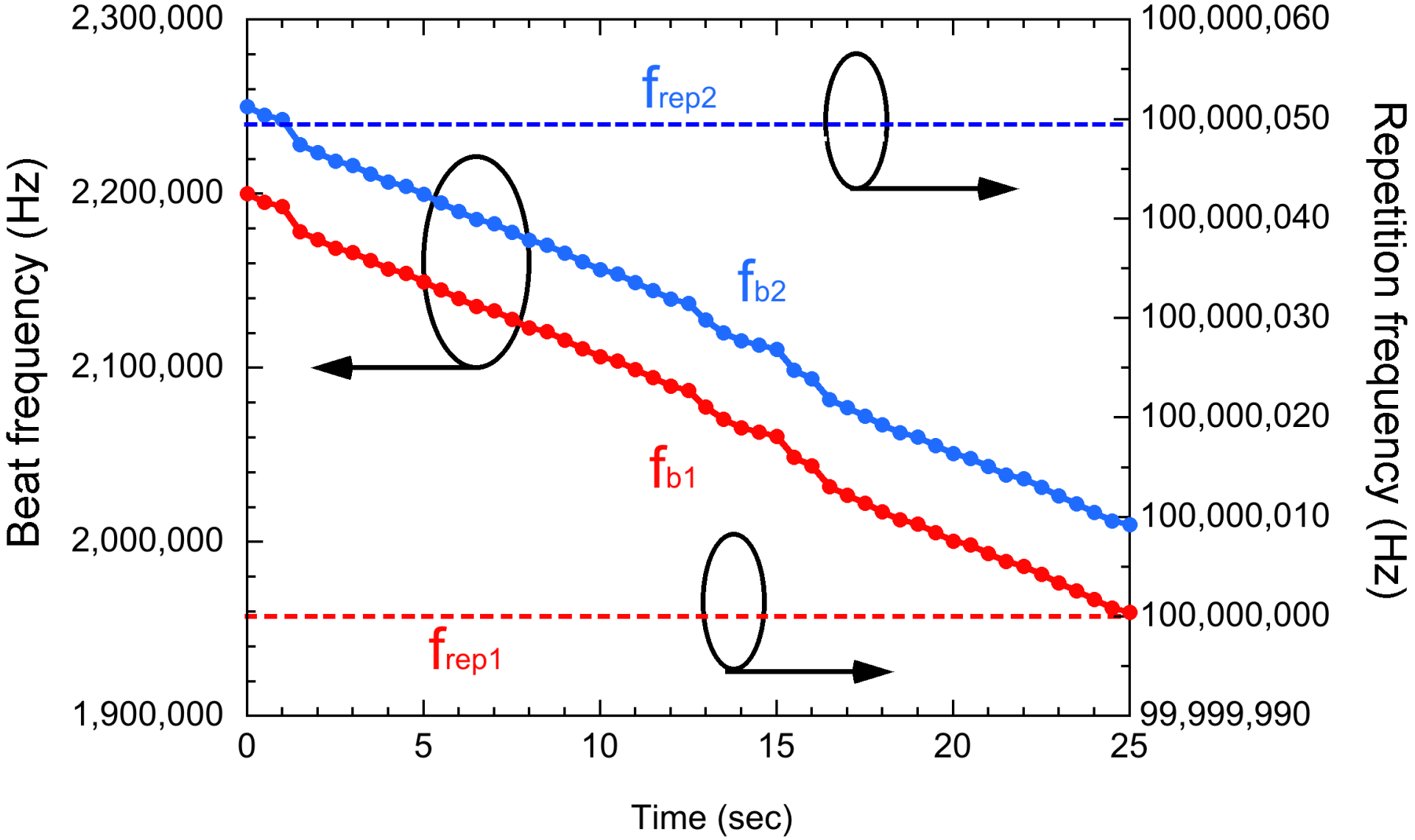
$$f_{THz} = mf_{rep1} - f_{b1} \quad \text{if } (f_{b2} - f_{b1})/(f_{rep2} - f_{rep1}) > 0$$

$$f_{THz} = mf_{rep1} + f_{b1} \quad \text{if } (f_{b2} - f_{b1})/(f_{rep2} - f_{rep1}) < 0$$

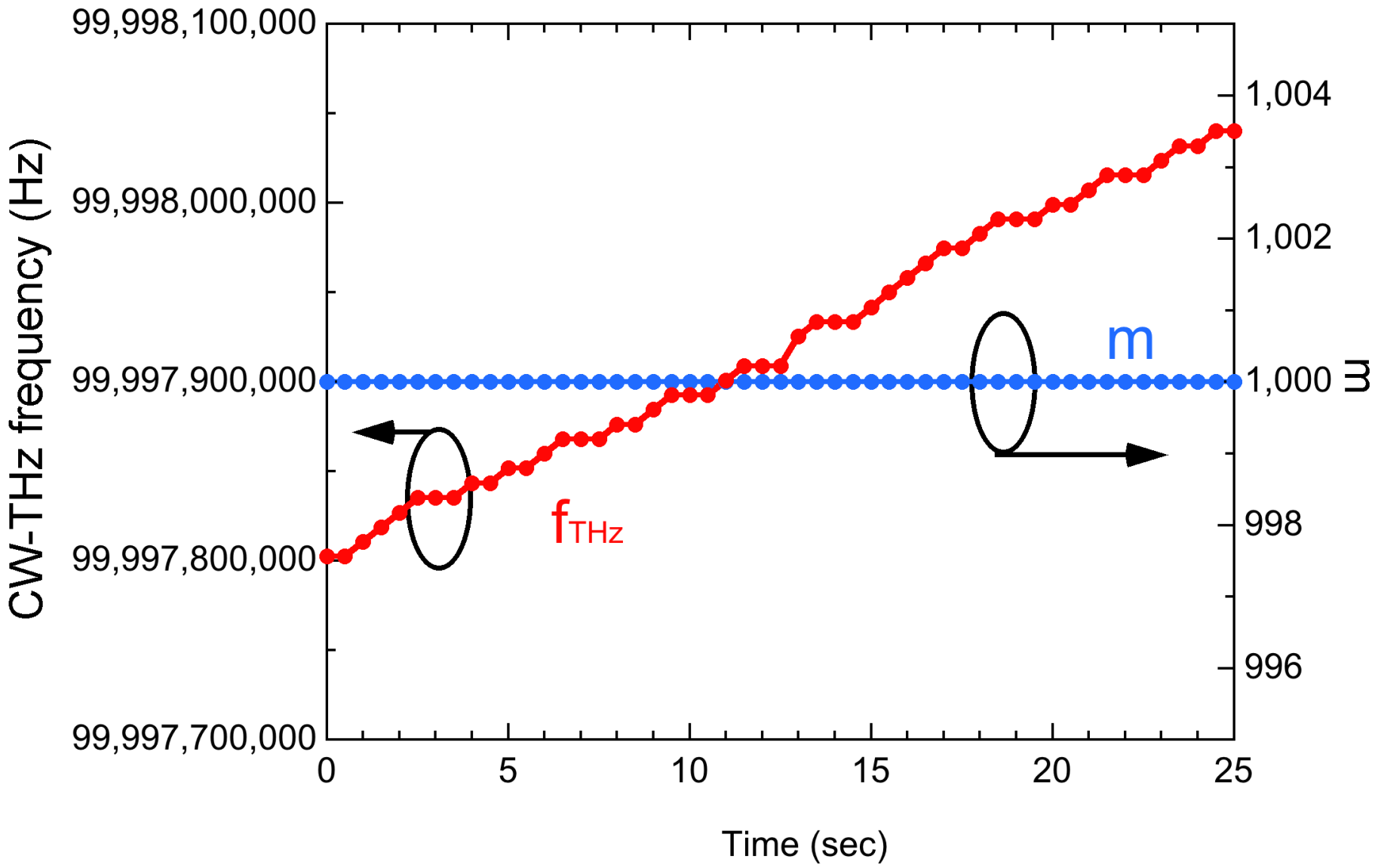
Experimental setup



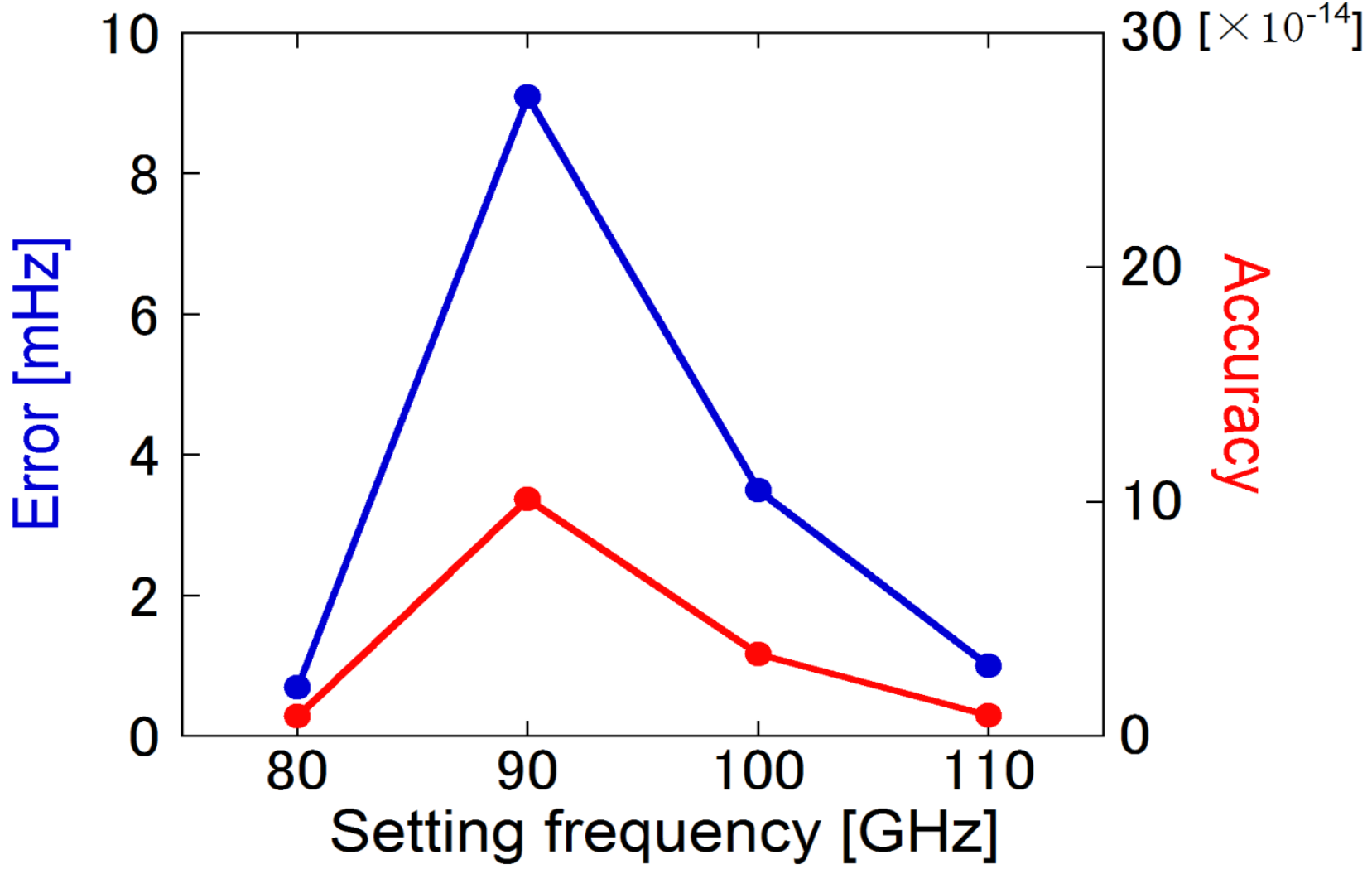
Real-time measurement of f_{rep} and f_b



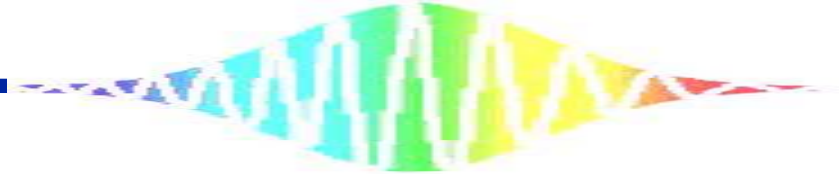
Real-time determination of m and f_{THz}



Accuracy of frequency measurement

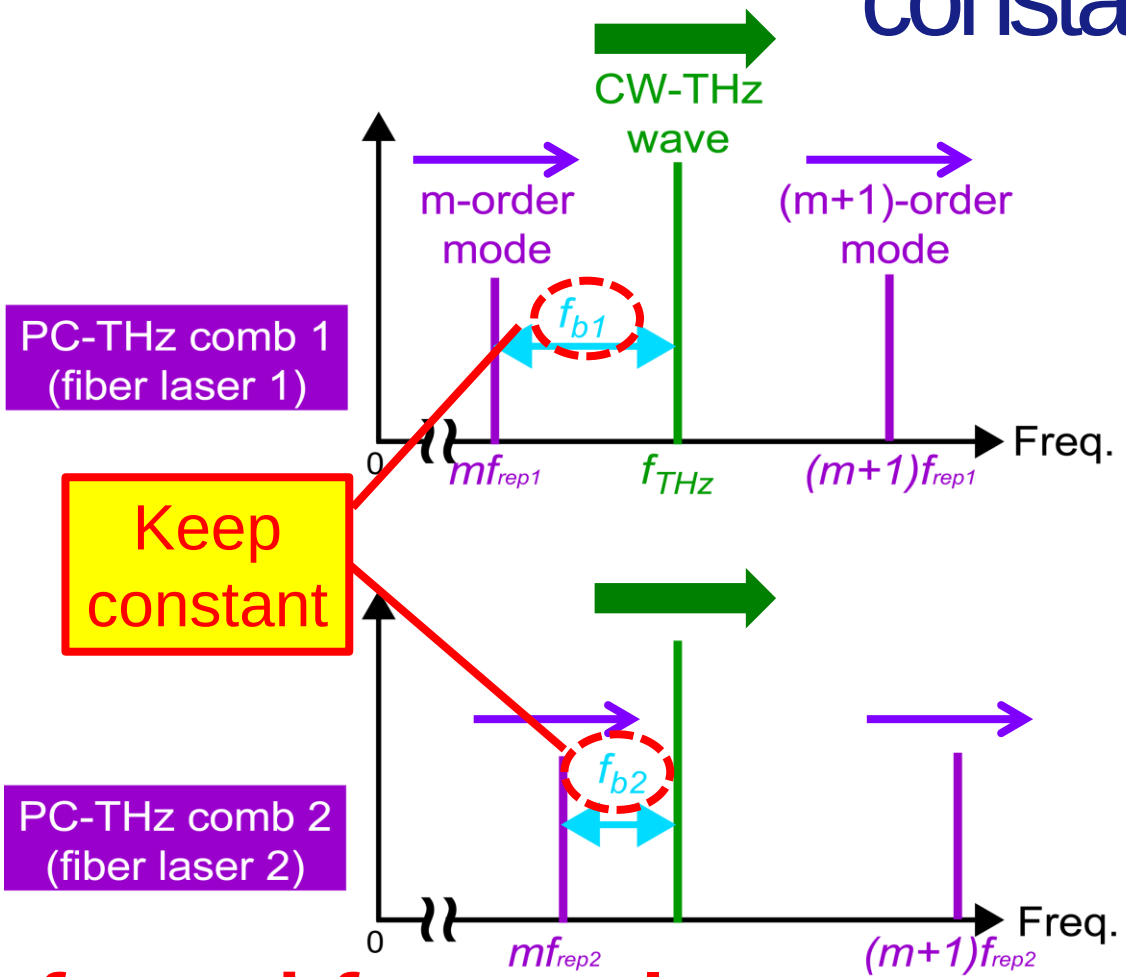


Mean precision=3.8*10^{-14}



(2) Real-time monitoring of frequency-swept CW-THz wave over frequency interval of PC-THz comb

Adjustment of f_{rep1} and f_{rep2} to keep f_{b1} and f_{b2} constant



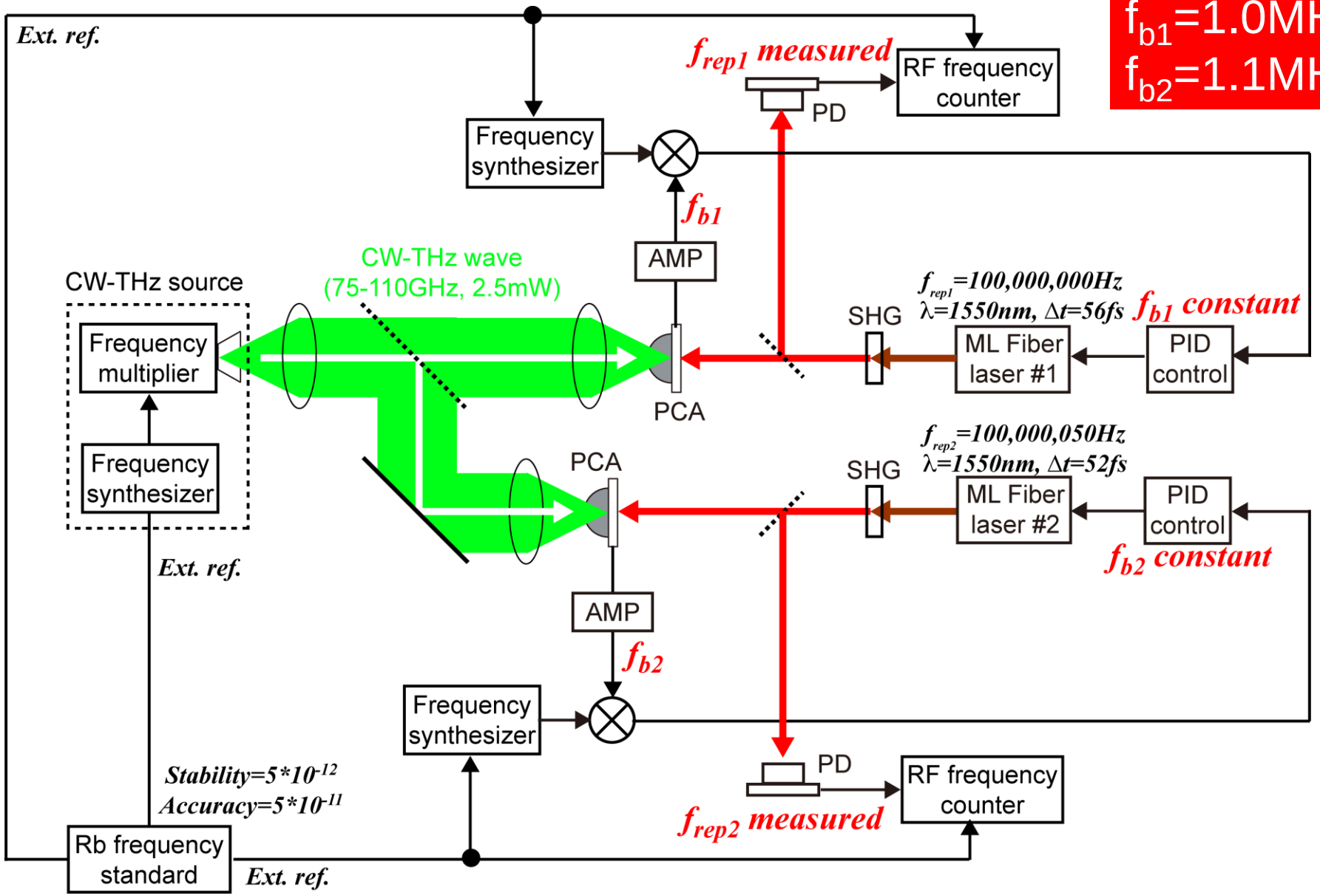
f_{rep1}, f_{rep2}: measured
f_{b1}, f_{b2}: fixed at known values

$$m = \frac{|f_{b2} - f_{b1}|}{|f_{rep2} - f_{rep1}|}$$

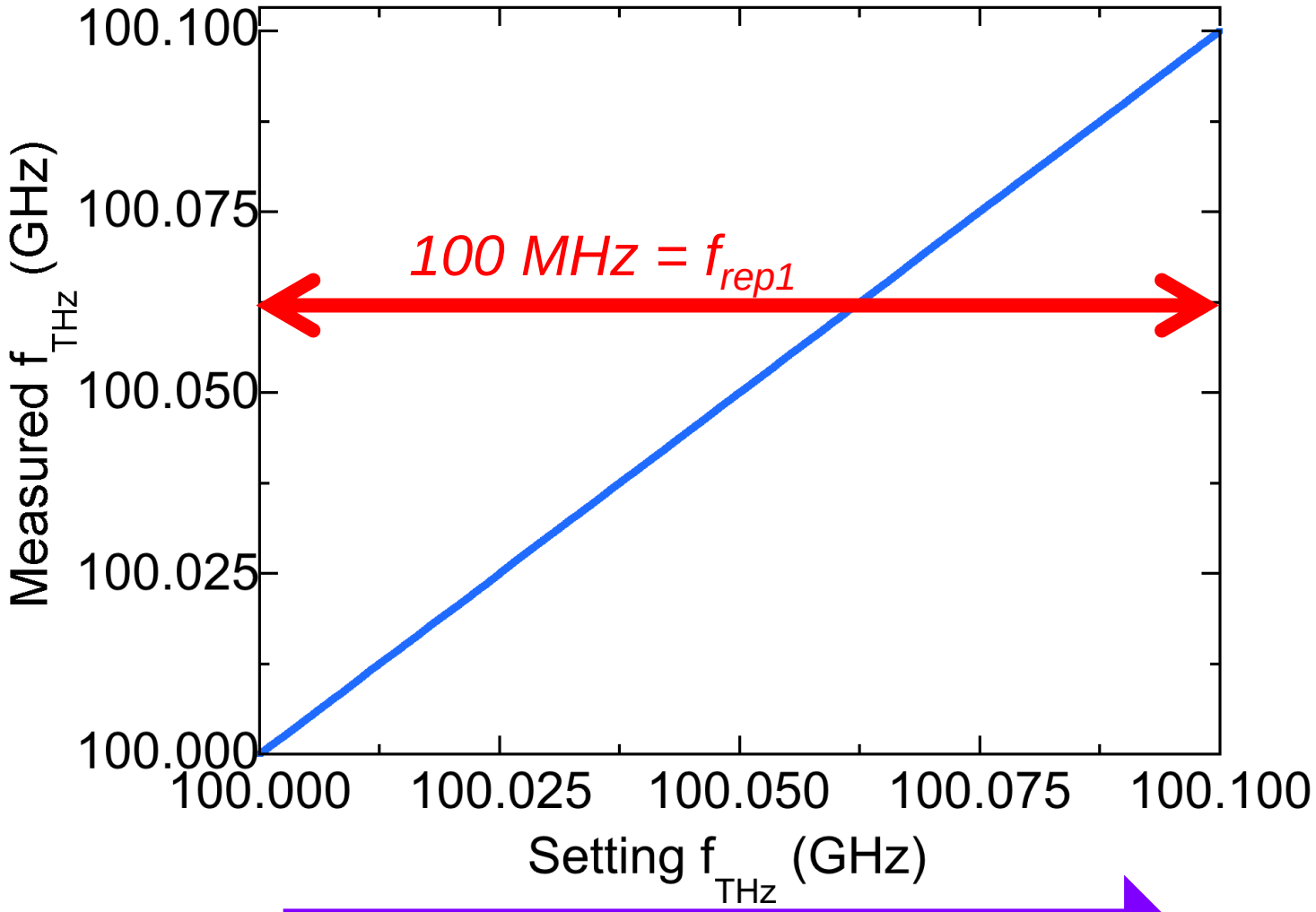
f_{b1} and f_{b2} are always constant even though f_{THz} is tuned over f_{rep1} and f_{rep2}

Experimental setup

f_{b1}=1.0MHz
f_{b2}=1.1MHz



Real-time monitoring of linearly frequency-swept CW-THz wave



Summary

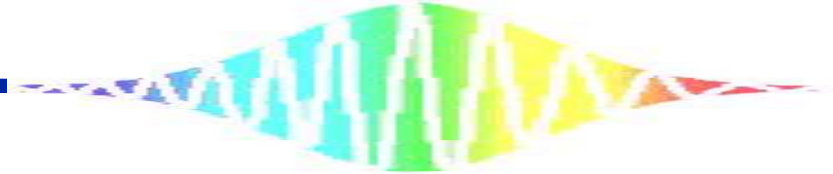
(1) Real-time determination of absolute frequency of CW-THz wave using dual PC-THz combs

(2) Real-time monitoring of CW-THz wave sweeping over frequency interval of PC-THz comb

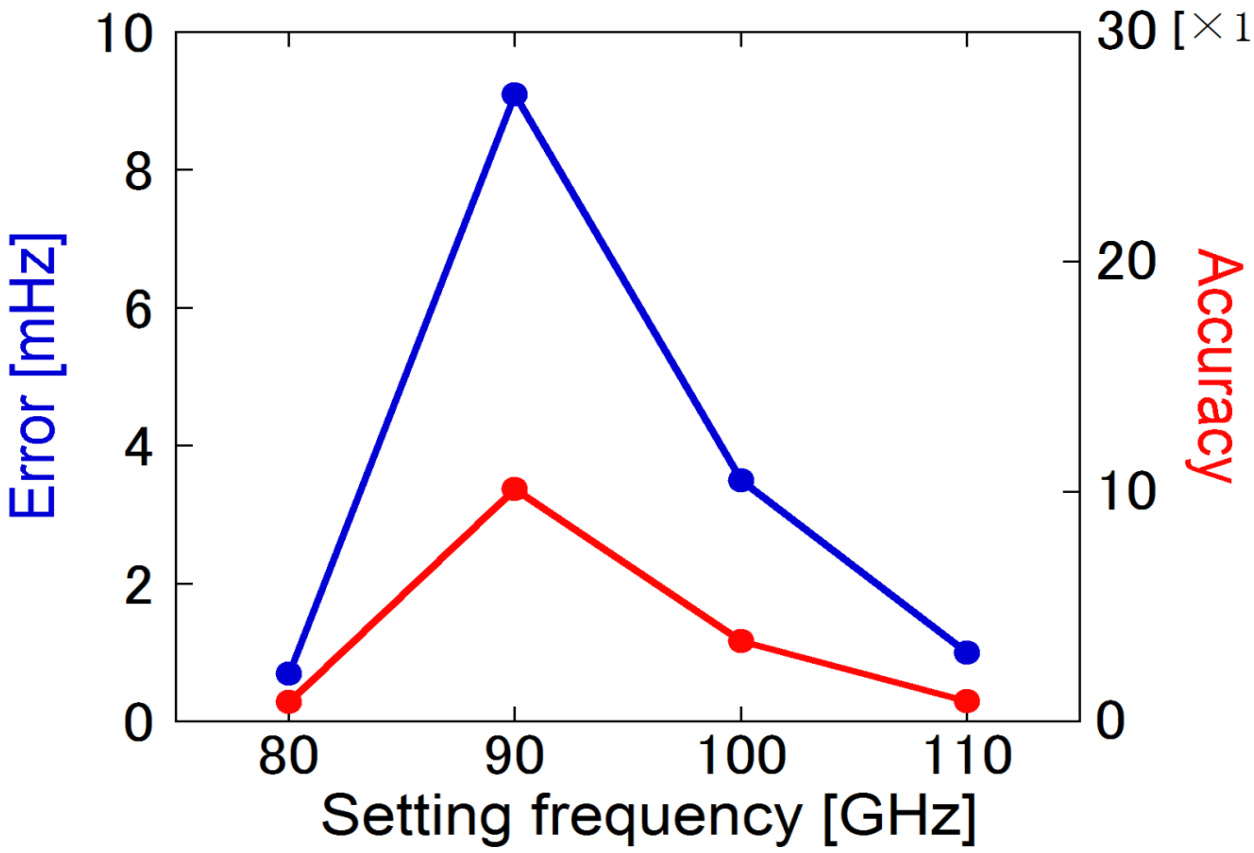
Future works

(1) Real-time determination of absolute frequency using a single PC-THz comb

(2) Direct coupling of PCA with 1.5μm fiber lasers, enabling us to construct a portable system



Accuracy of absolute frequency measurement



Estimation of measurement error

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

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

Δf_{rep1} = 400μHz
Δf_{beat1} = 21mHz
m = 800~1100

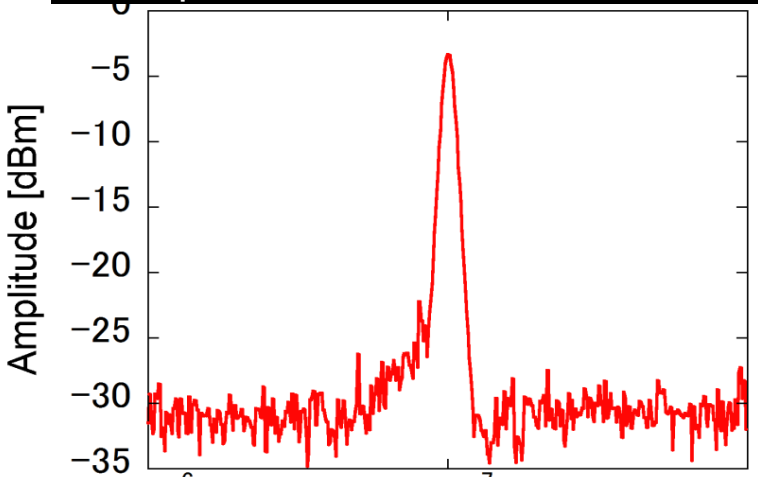
↓

Δf_{THz} = 341~461mHz

Mean precision=$3.8*10^{-14}$

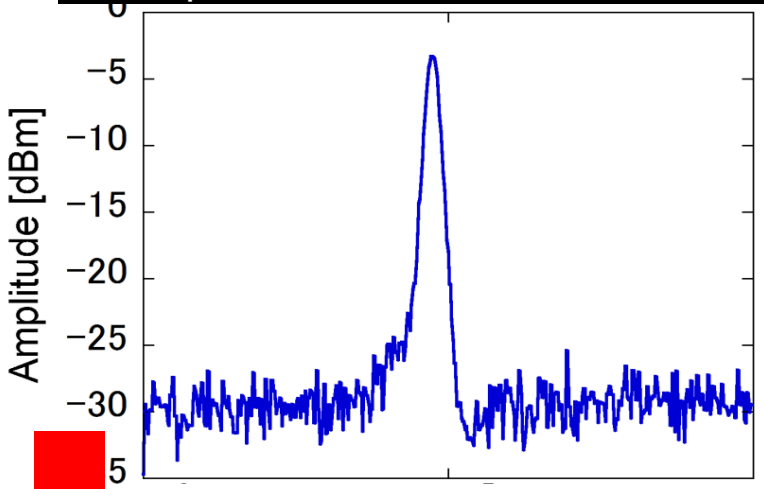
Beat signals between CW-THz wave and dual PC-THz comb

PC-THz comb 1
(f_{rep1} = 100,000,000 Hz)



f_{b1}=10,004,000.01Hz

PC-THz comb 2
(f_{rep2} = 100,000,050 Hz)



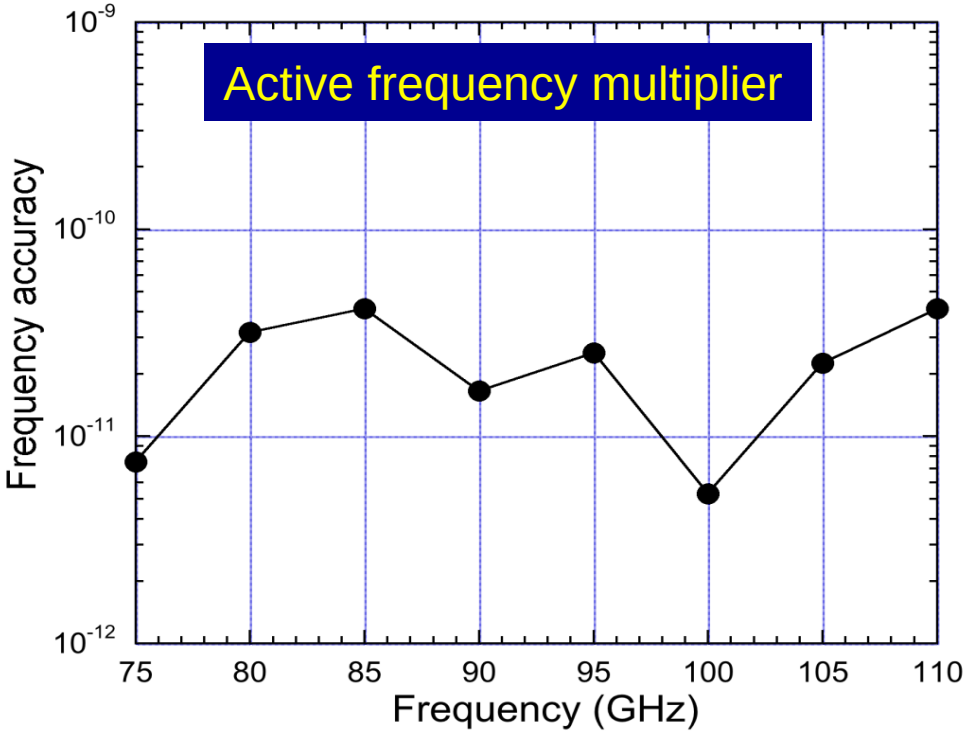
f_{b2}=9,953,700.002Hz

Real-time determination!

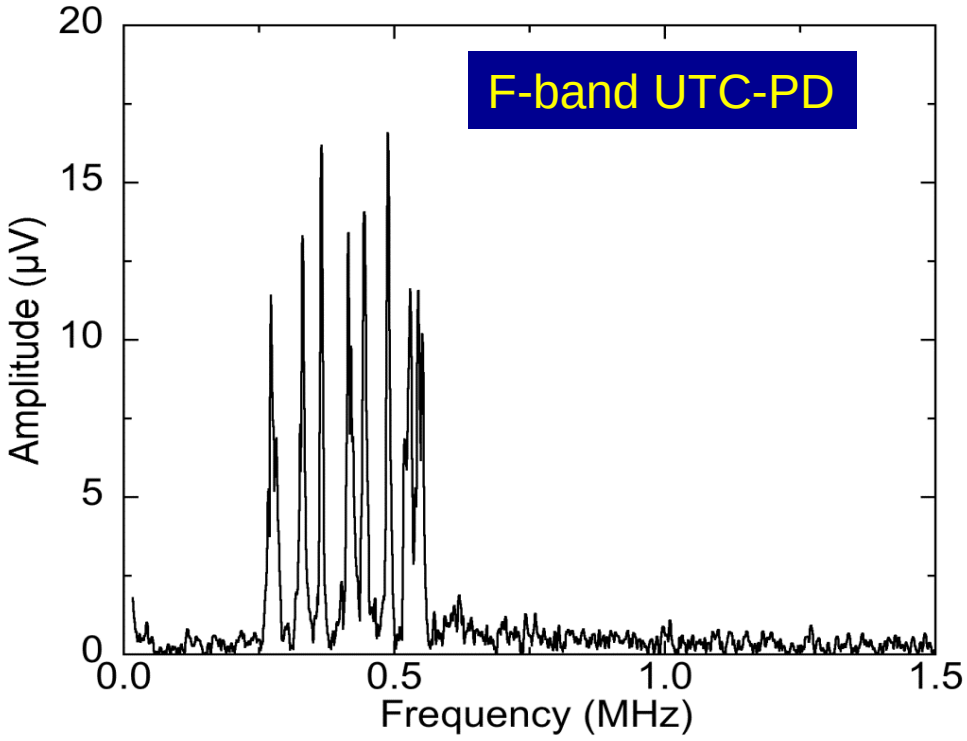
$m = |f_{beat1}-f_{beat2}|/|f_{rep1}-f_{rep2}|$
$=|10,004,000.01-9,953,700.002|/|100,000,000-100,000,050| = 1006$
$f_{THz} = mf_{rep1}+f_{beat1}) = 1006*100,000,000+10,004,000.01 = 100,610,004,000Hz$

Previous study

Absolute frequency measurement



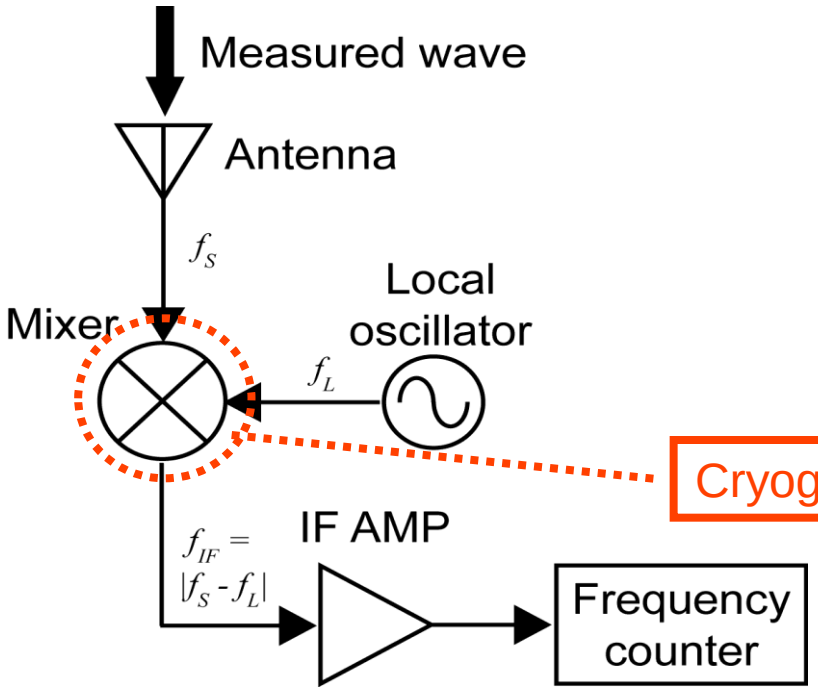
Real-time monitoring of CW-THz wave



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

Conventional method

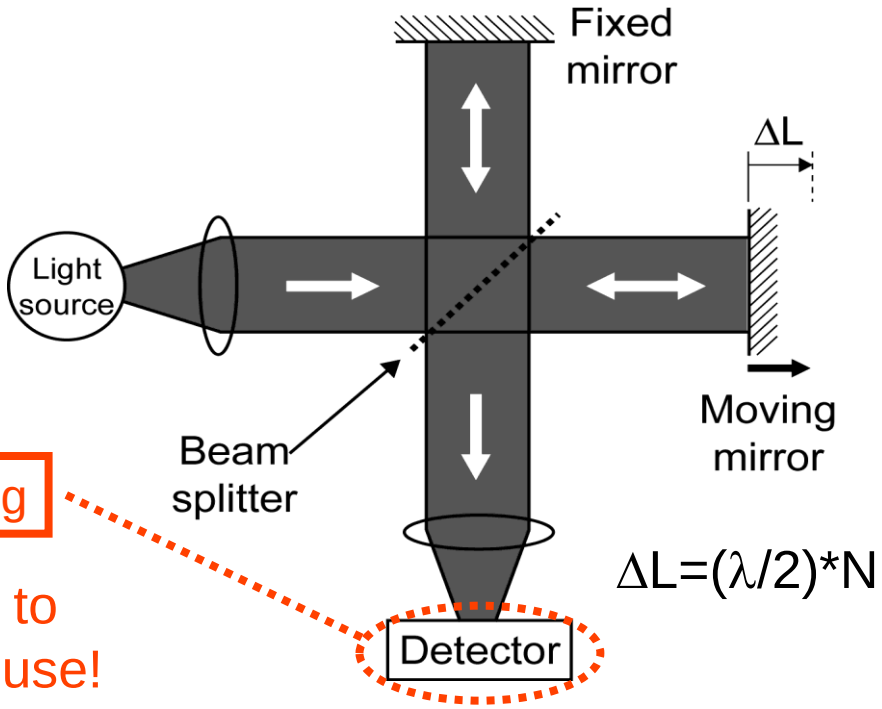
Electrical heterodyned method



Cryogenic cooling

Obstacle to practical use!

Optical interferometric method



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

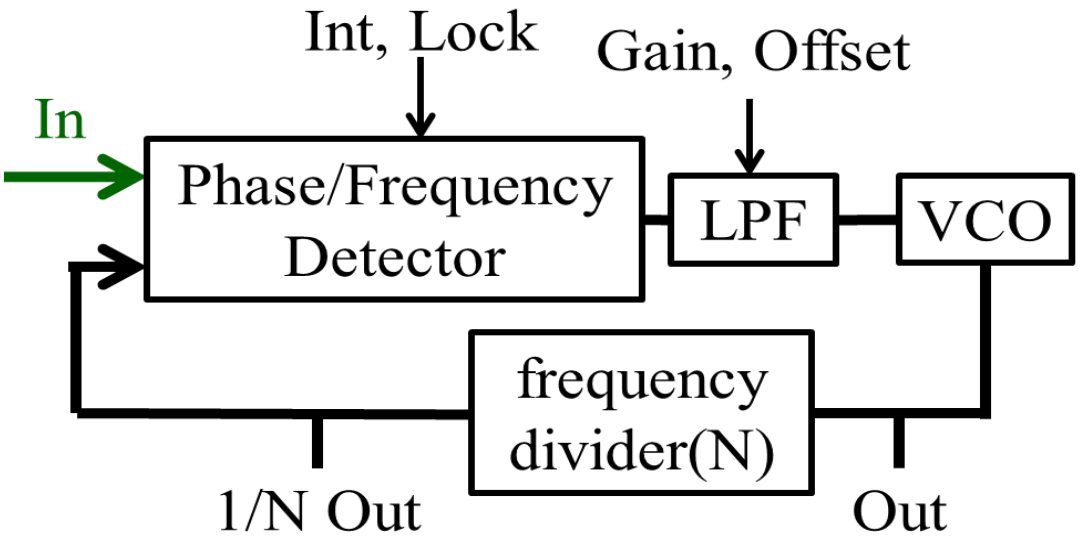
→Requirement of new method optimized for THz wave!

Tracking Oscillator

位相同期により入力信号を増幅

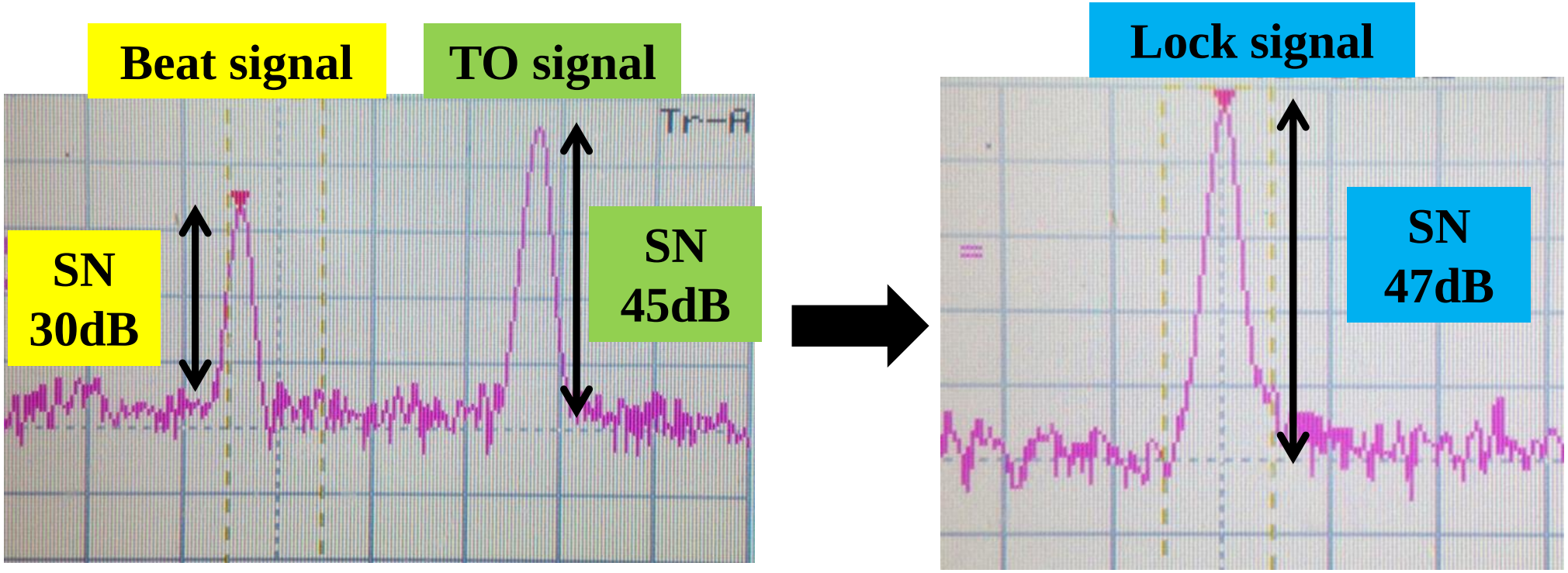
入力周波数の変動はVCOがトラッキングし, 位相同期を維持

SN比の向上



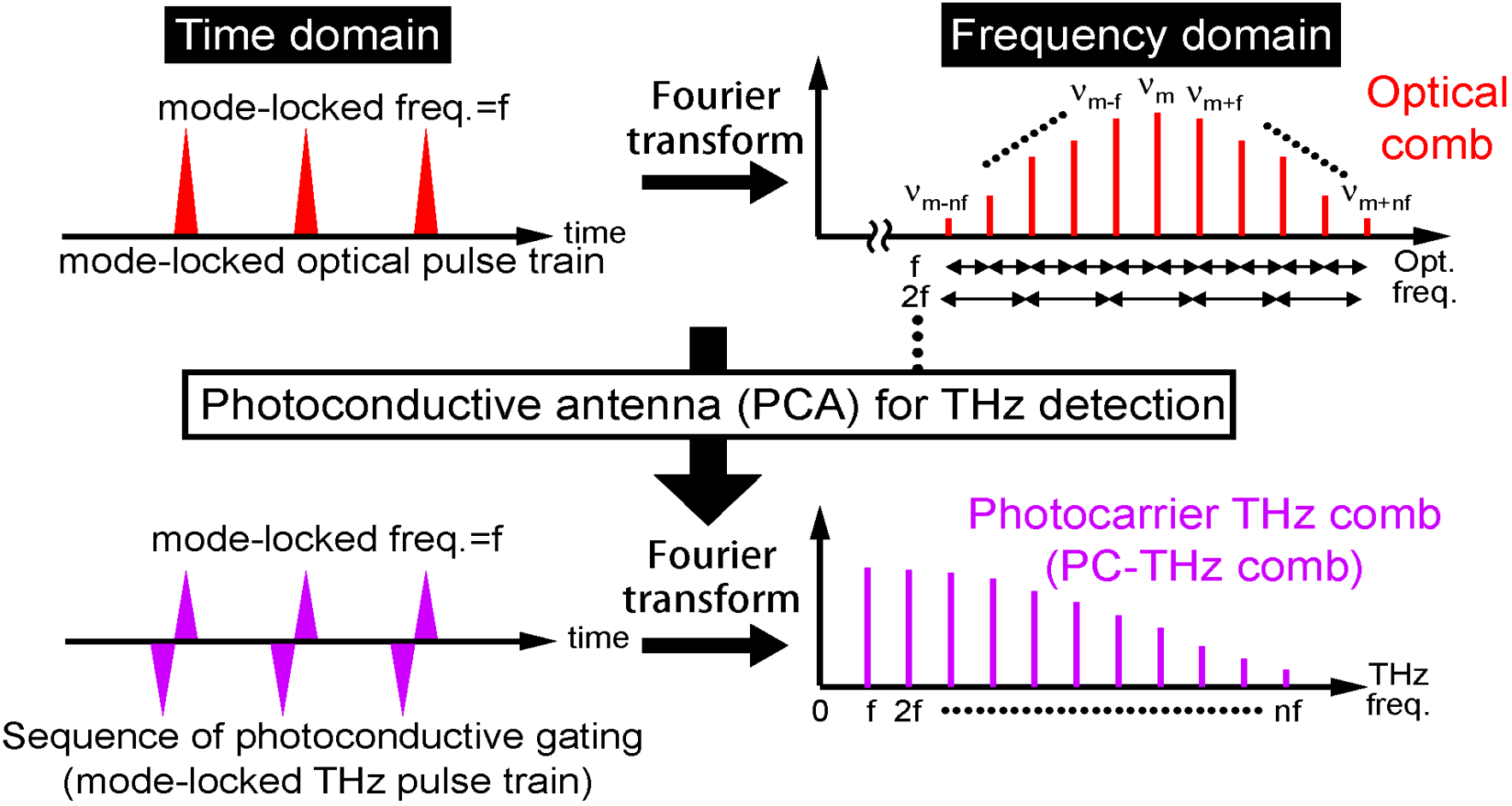
トラッキングオシレーターを用いて絶対周波数のリアルタイム測定を目指す

Tracking Oscillator の特性評価



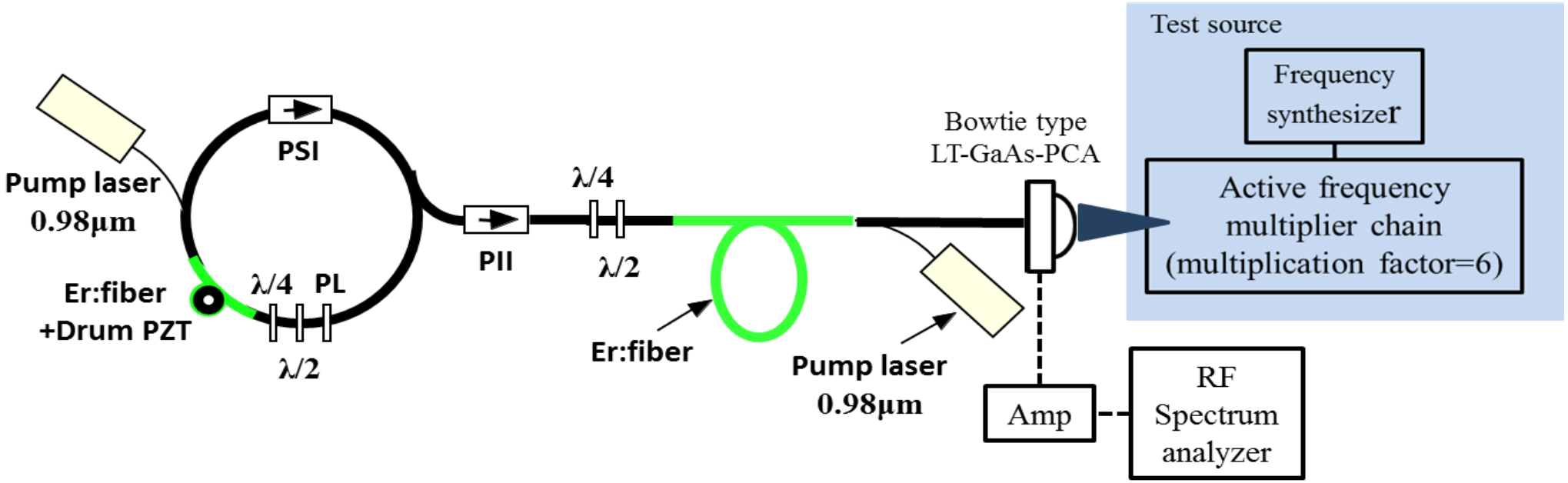
最低30dB (RBW10kHz) のビート信号においてトラッキングオシレーターでロック可能

Optical comb and THz comb



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

② Experimental setup



Er:fiber laser

Center wavelength 1550nm

Repetition rate 56MHz

Pulse width 47fs

Average power 189mW