Background

Frequency is a fundamental physical quantity of electromagnetic wave

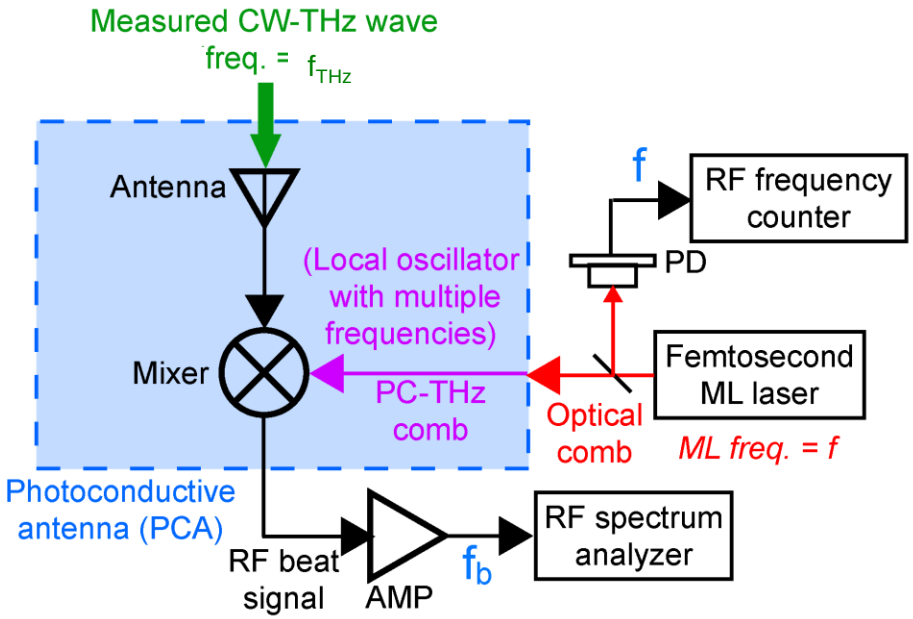
Maintenance of THz frequency metrology is required for various THz applications

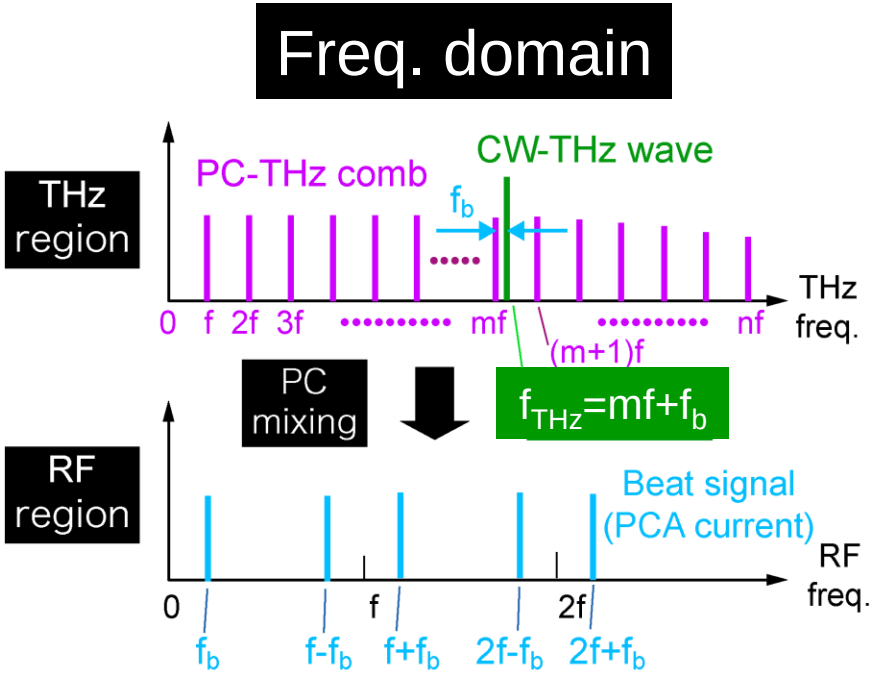
Advent of practical CW-THz sources (THz-QCL, photomixing with UTC-PD, RTD etc)

Precise frequency measurement of CW-THz wave is required!

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

THz spectrum analyzer (1)



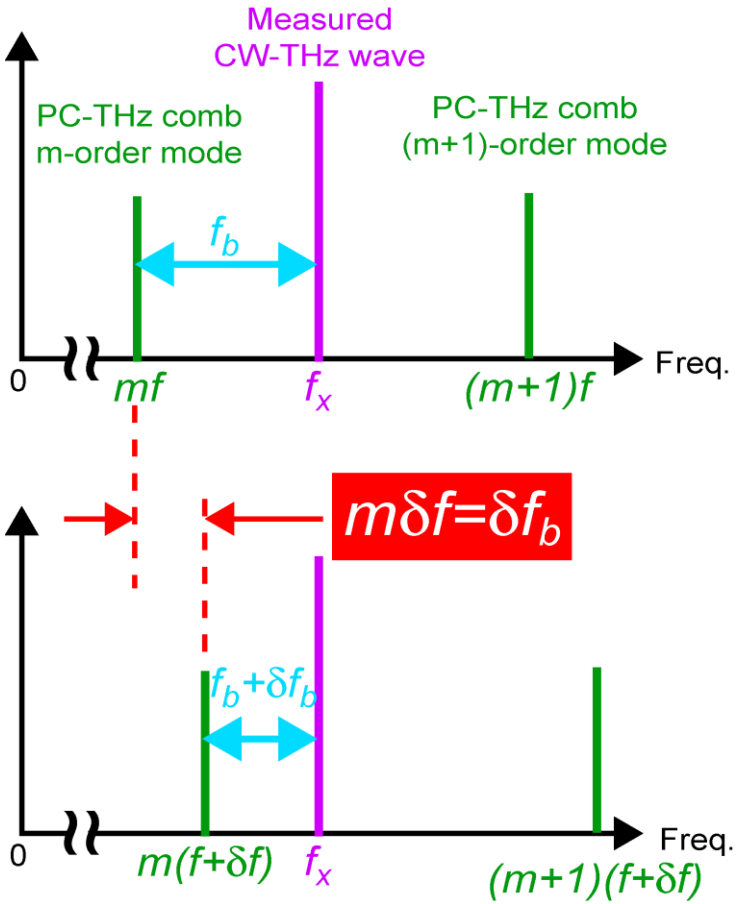


$$f_{THz}=mf \pm f_b$$

m: order of comb mode
f: ML frequency
f_b: beat frequency

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

THz spectrum analyzer (2)



Shift of ML freq. by δf
($f \rightarrow f+\delta f$)

$$m = \frac{|\delta f_b|}{|\delta f|}$$

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

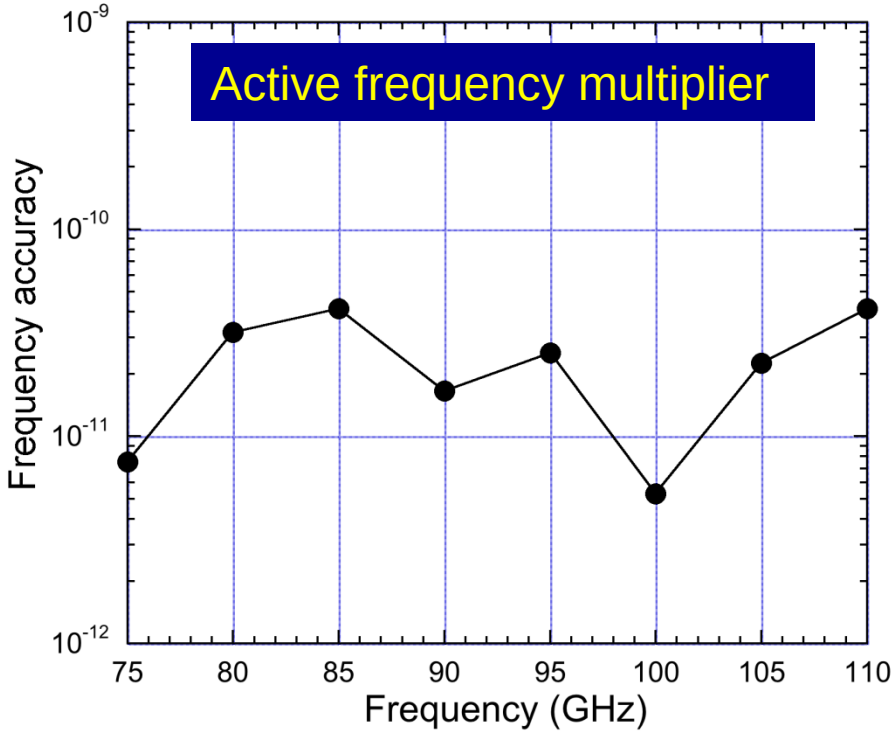
$$f_{THz} = mf - f_b \qquad (\delta f_b/\delta f > 0)$$

$$f_{THz} = mf + f_b \qquad (\delta f_b/\delta f < 0)$$

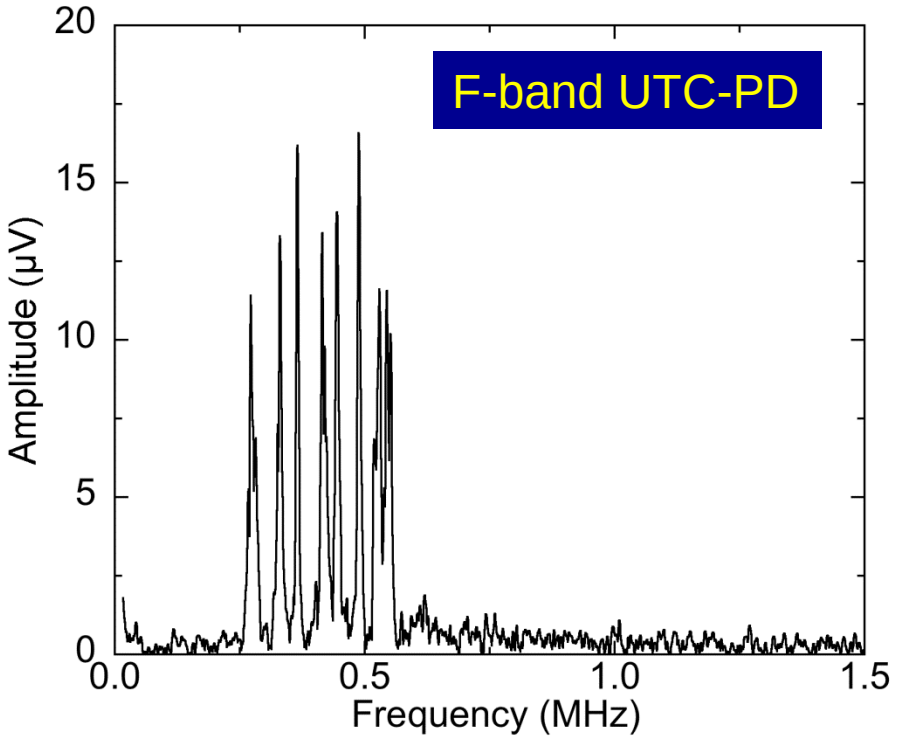
Previous study

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

Absolute frequency measurement



Real-time monitoring of CW-THz wave



Problems of previous studies for practical use

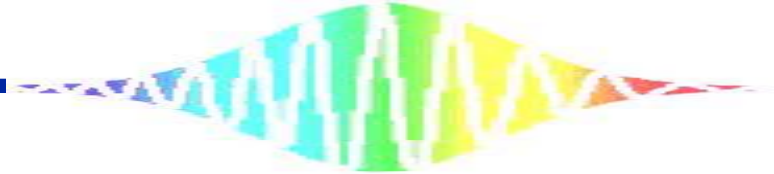
(1) 2-step measurements of beat signal for absolute frequency determination ☞ **Not real-time!**

(2) Coupling of PCA with 1.5-μm fiber laser light using free-space optics ☞ **Not portable!**

Present talk

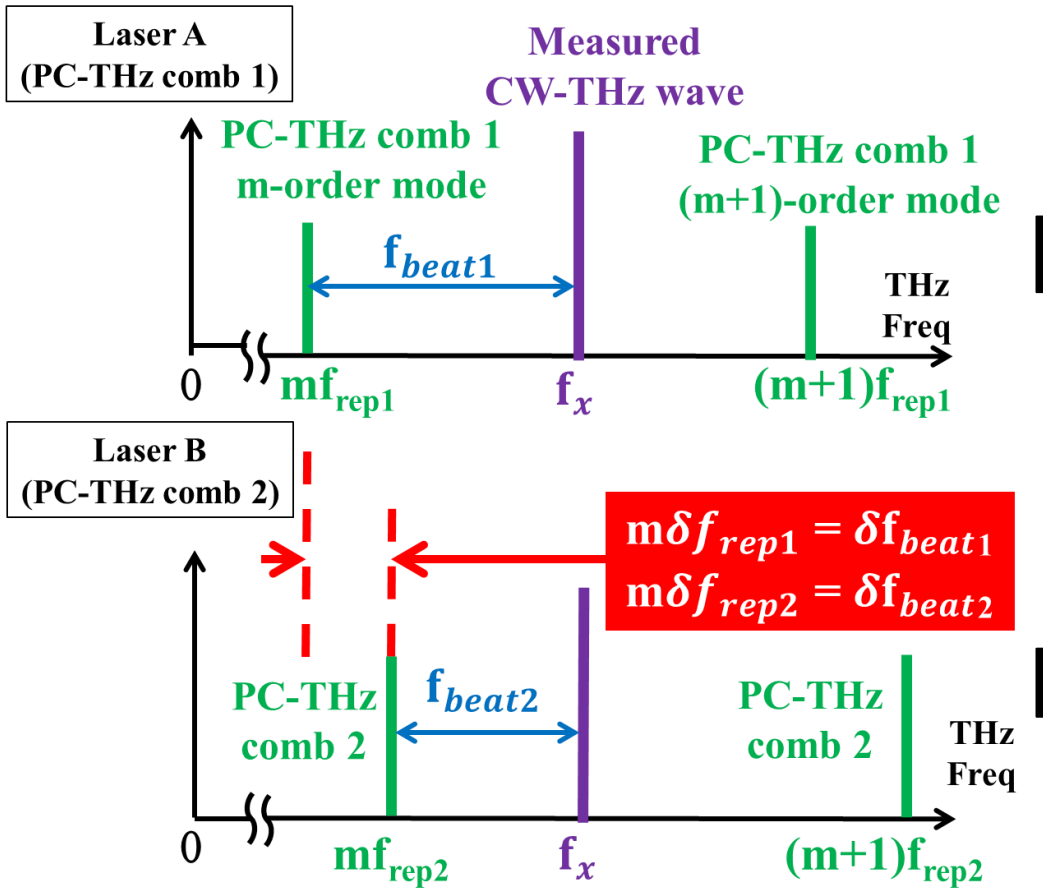
(1) **Real-time determination** of absolute frequency using dual PC-THz combs

(2) **Direct coupling** of LT-GaAs-PCA with output fiber tip of 1.5μm fiber laser



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

Real-time determination of absolute frequency

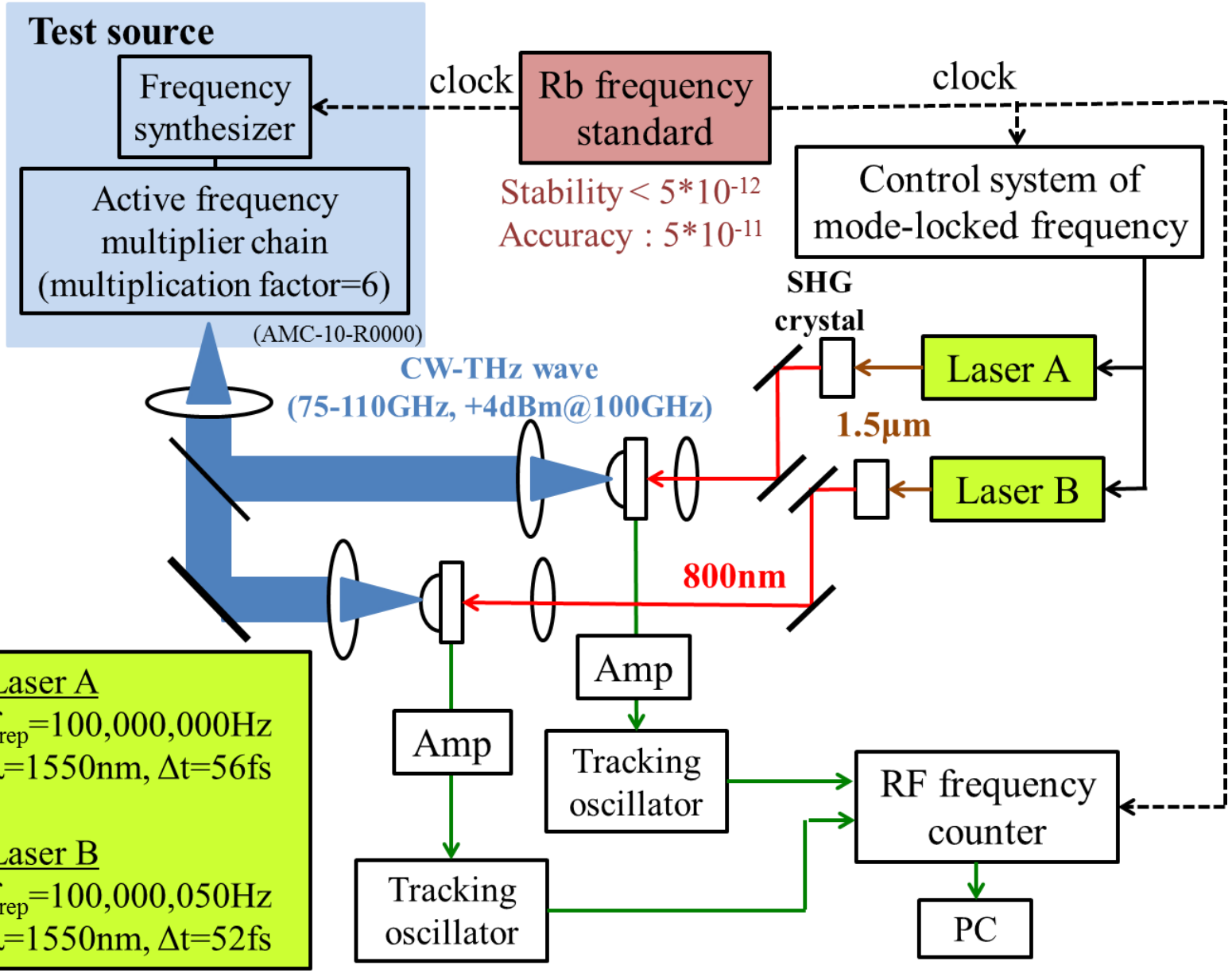


$$m = \frac{\left| f_{beat1} - f_{beat2} \right|}{\left| f_{rep1} - f_{rep2} \right|}$$

$$f_{THz} = mf_{rep1} - f_{beat1} \qquad (\delta f_{beat} / \delta f_{rep} > 0)$$

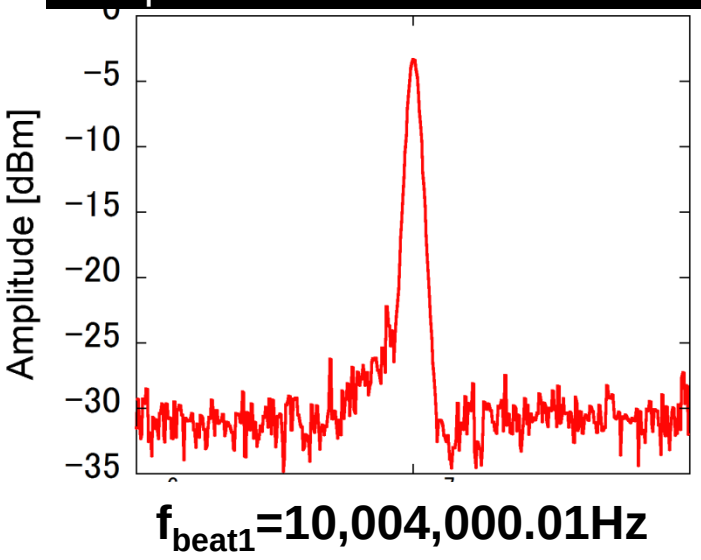
$$f_{THz} = mf_{rep1} + f_{beat1} \qquad (\delta f_{beat} / \delta f_{rep} < 0)$$

Experimental setup



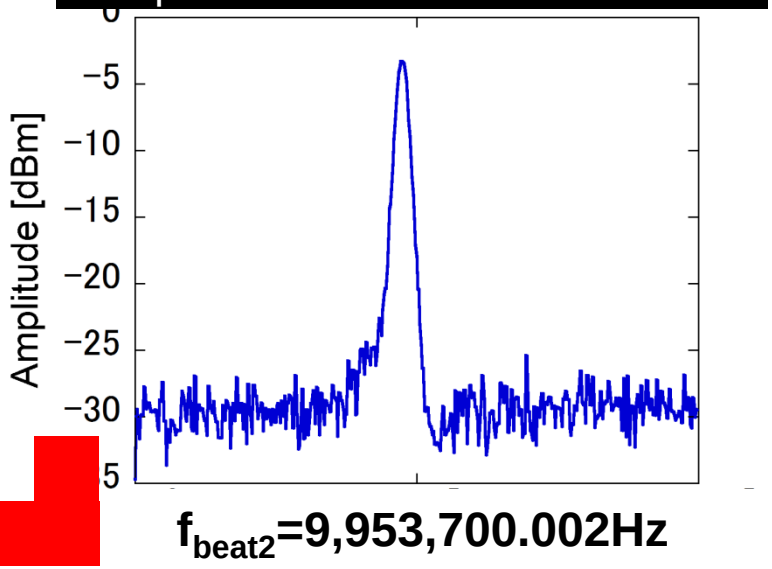
Beat signals between CW-THz wave and dual PC-THz comb

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



f_{beat1}=10,004,000.01Hz

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

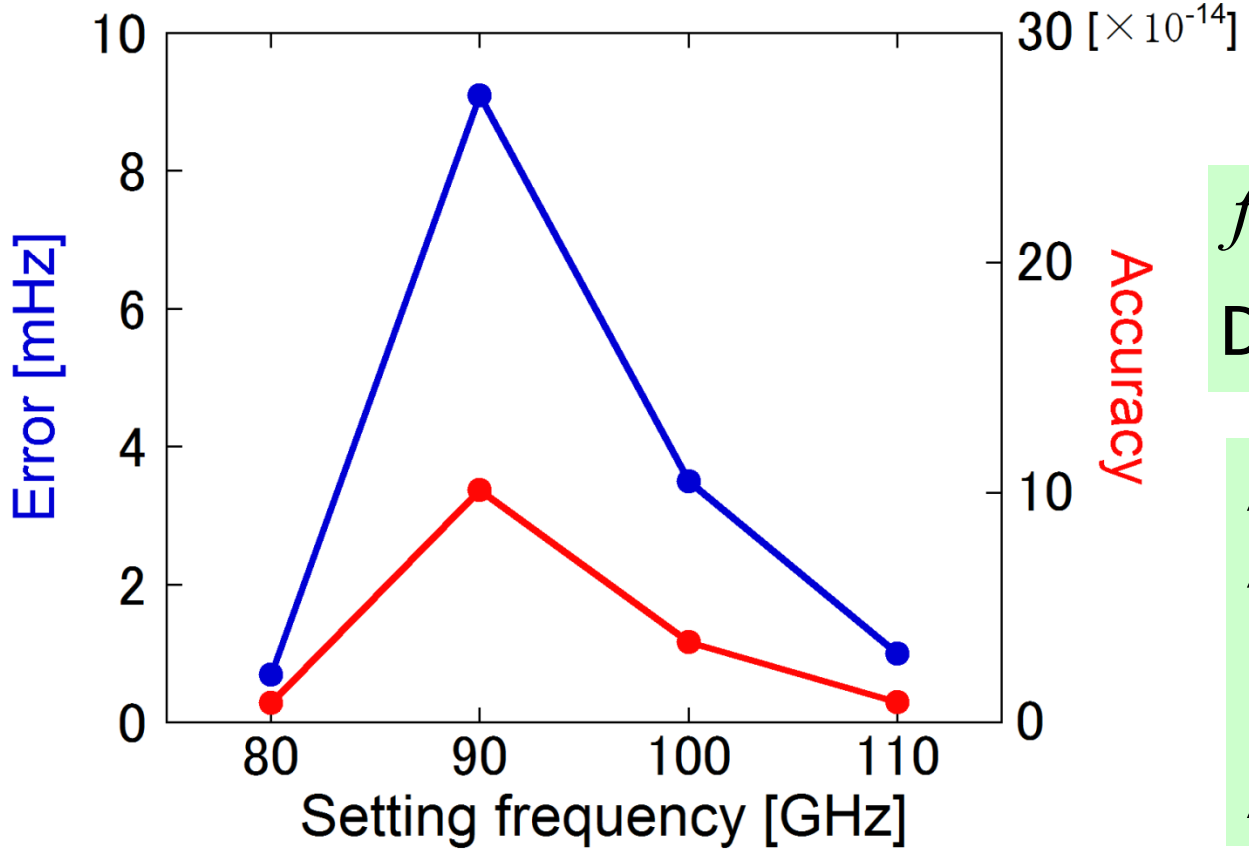


f_{beat2}=9,953,700.002Hz

Real-time determination!

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

Accuracy of absolute frequency measurement



Estimation of measurement error

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

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

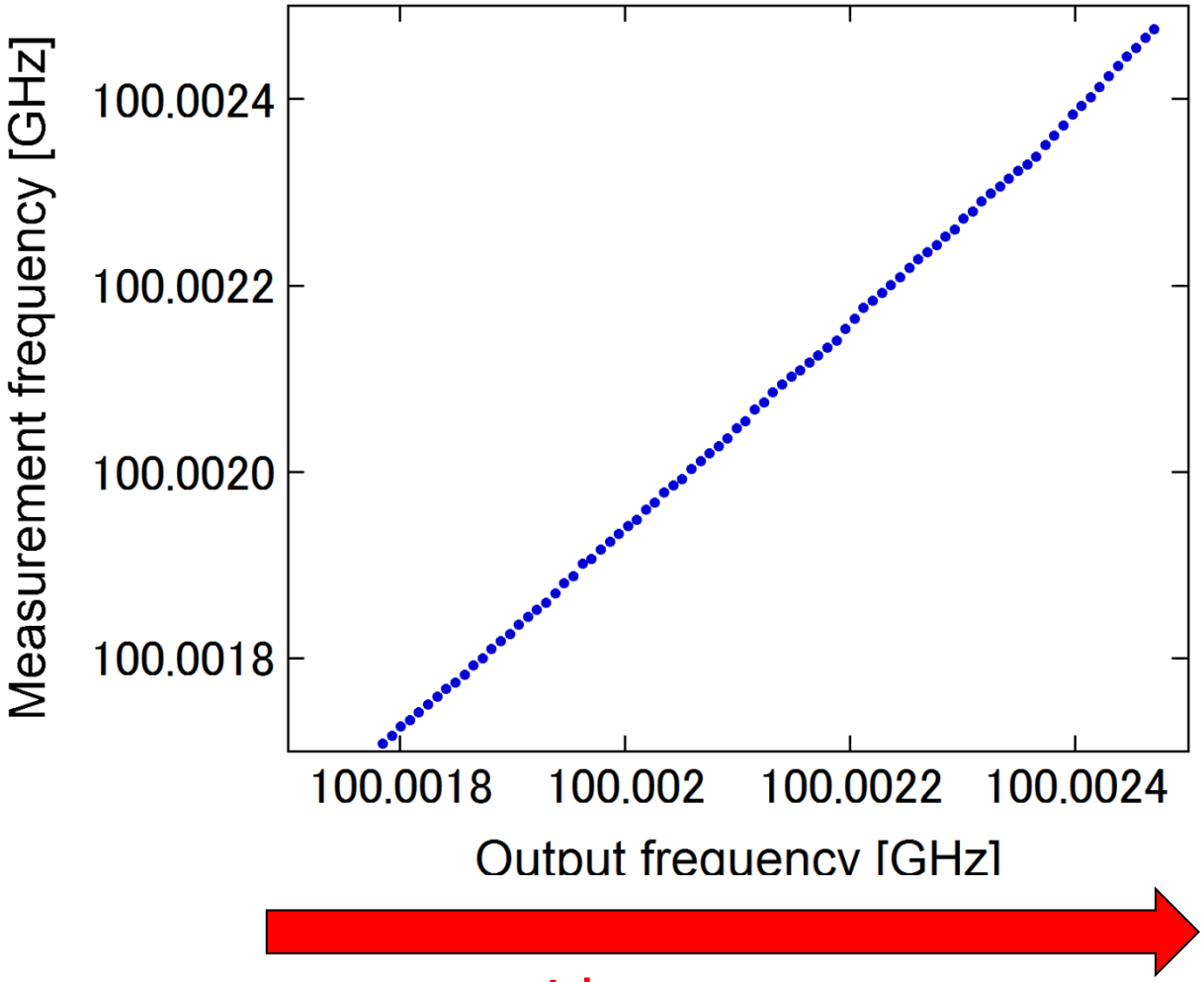
Δf_{rep1} = 400μHz
Δf_{beat1} = 21mHz
m = 800~1100

↓

Δf_{THz} = 341~461mHz

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

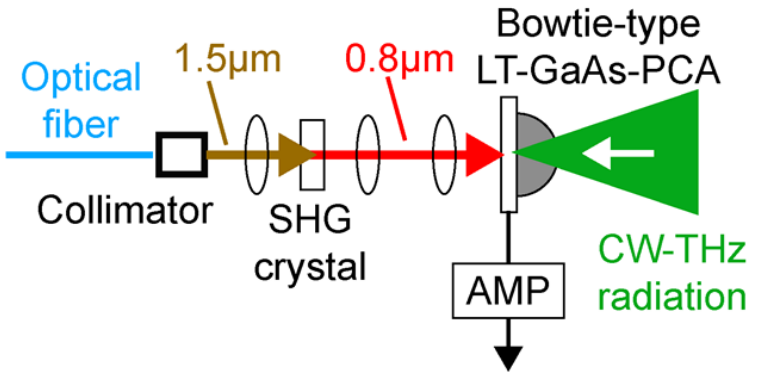
Real-time monitoring of linearly frequency-swept CW-THz wave



(2) Direct coupling of LT-GaAs-PCA with output fiber tip of 1.5μm fiber laser

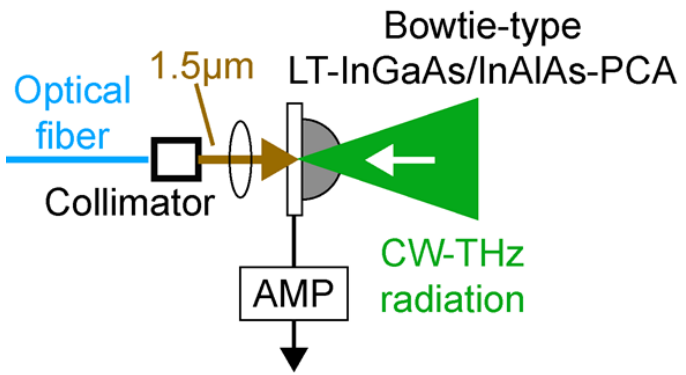
Coupling methods of PCA with1.5-μm light

(1) SHG & lenses @ LT-GaAs PCA



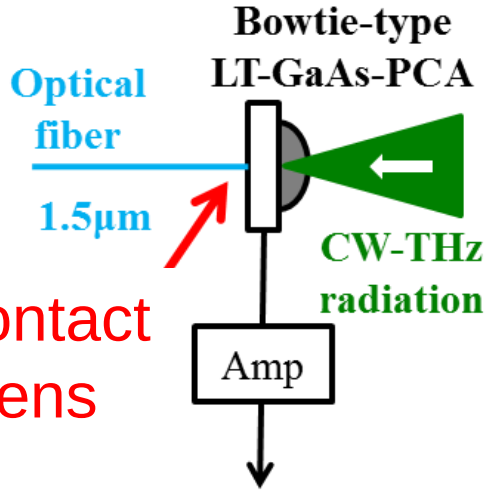
Several free-space optics required

(2) lenses @ LT-InGaAs PCA



Low sensitivity

(3) No optical components @ LT-GaAs PCA



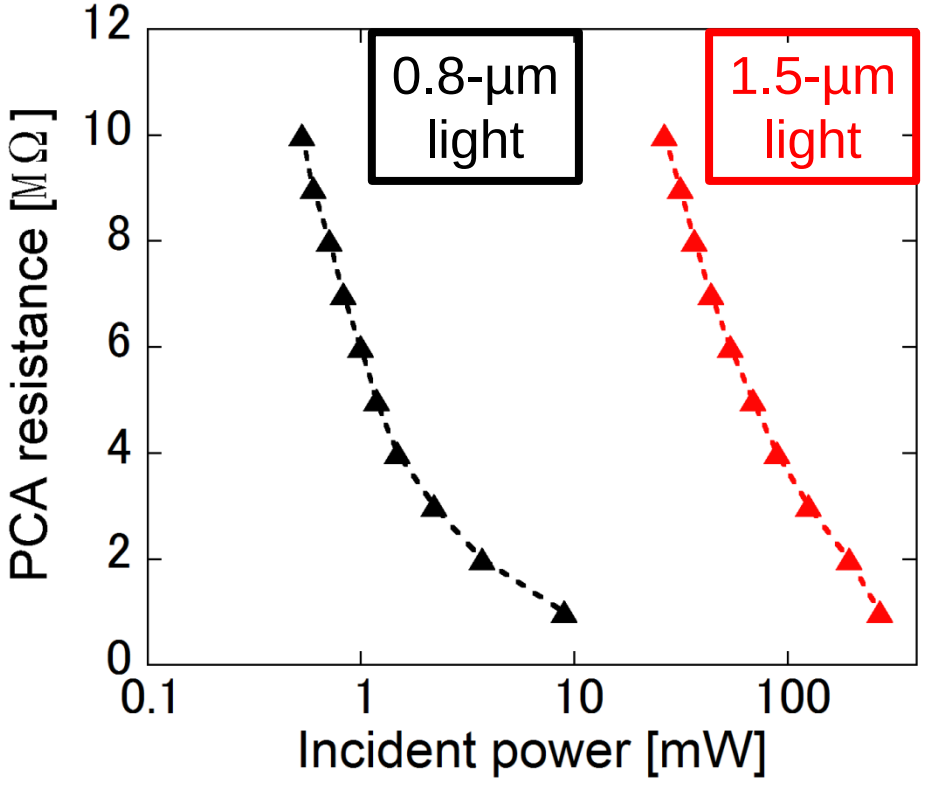
Direct contact without lens

No free-space, no optics, and moderate sensitivity

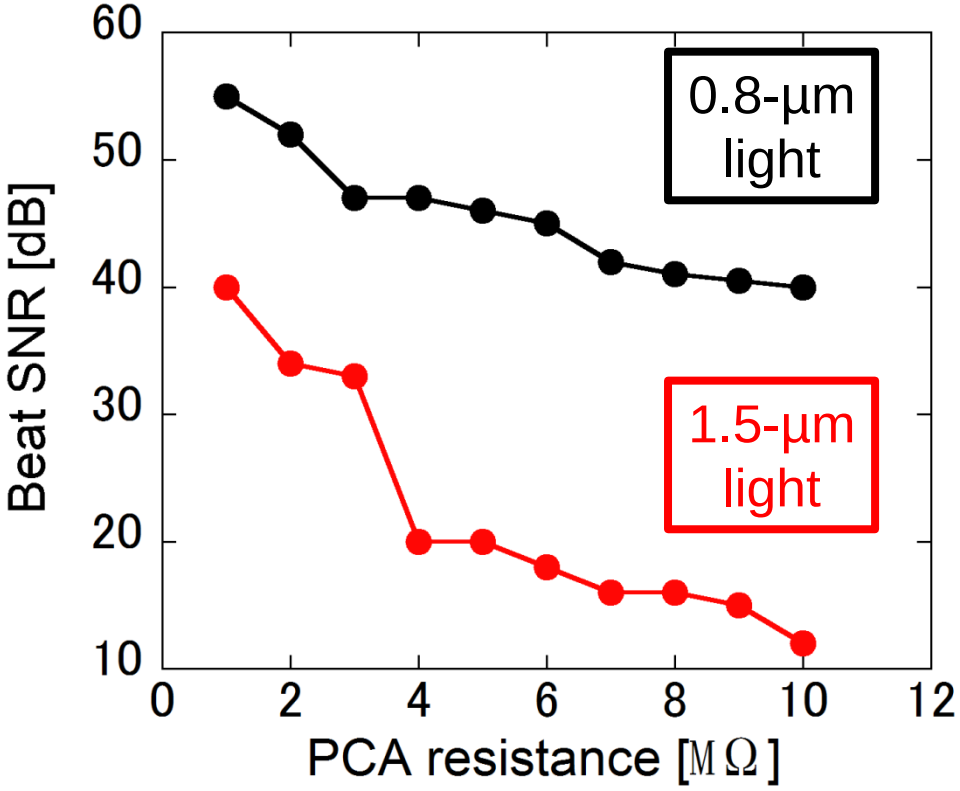
Comparison between 0.8-μm and 1.5-μm lights

Beat frequency 100kHz (amp 100kHz, 50MΩ), RBW=3kHz

Dependence of PCA resistance on incident power

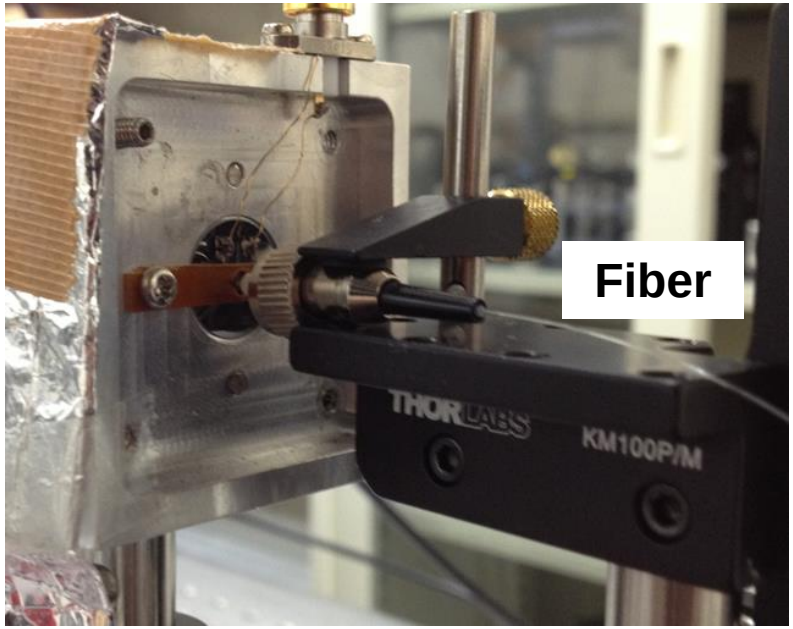


Dependence of beat SNR on PCA resistance

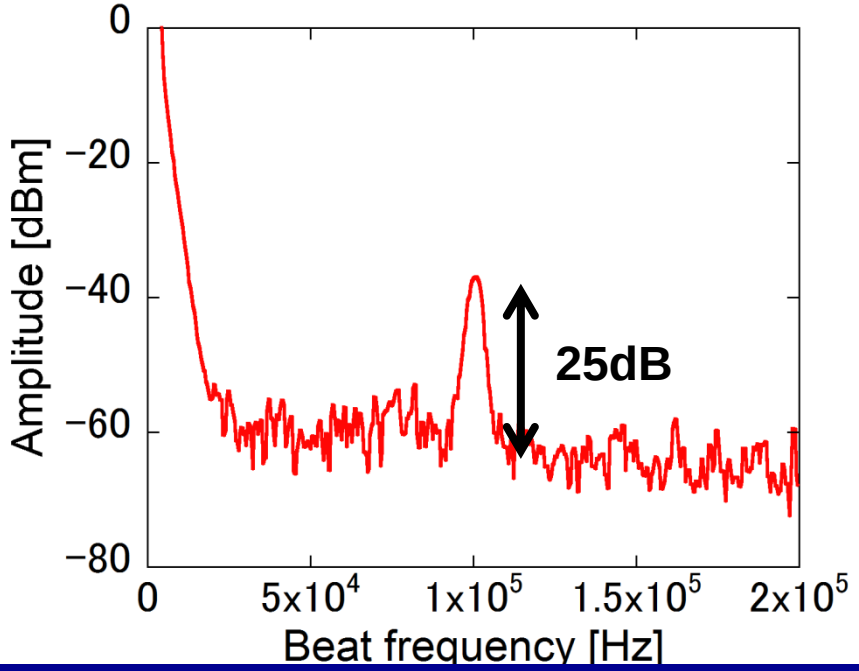


Results

Direct fiber coupling without lens
(P_{mean} = 189mW, f_{rep} = 56MHz)



RF spectrum of f_b beat signal
(f_{beat} = 100kHz)



Direct fiber coupling enables us to construct compact, robust, maintenance-free THz spectrum analyzer for portable use in practical applications!

Summary

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

(2) Direct coupling of LT-GaAs-PCA with output fiber tip of 1.5μm fiber laser, enabling us to construct a portable system

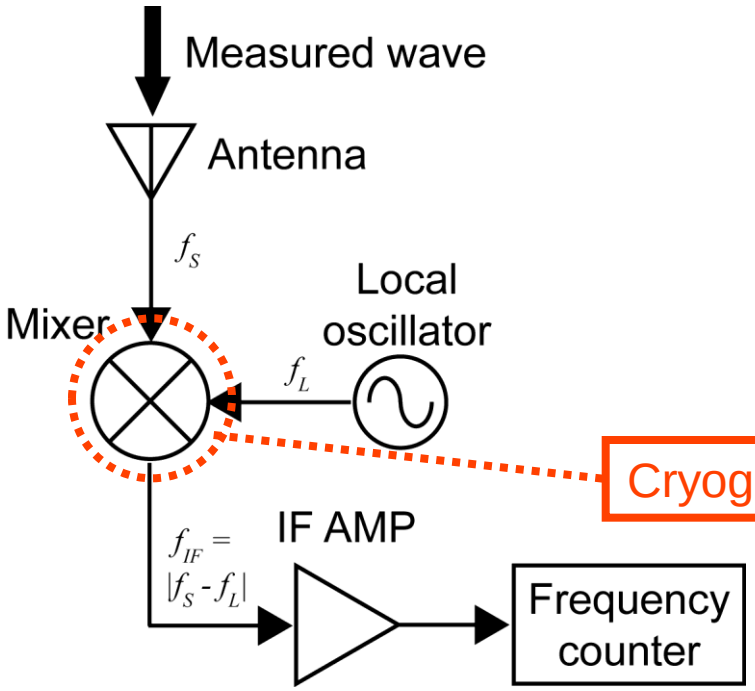
Future works

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

(2) Integration of PCA, fiber tip, and amplifier

Conventional method

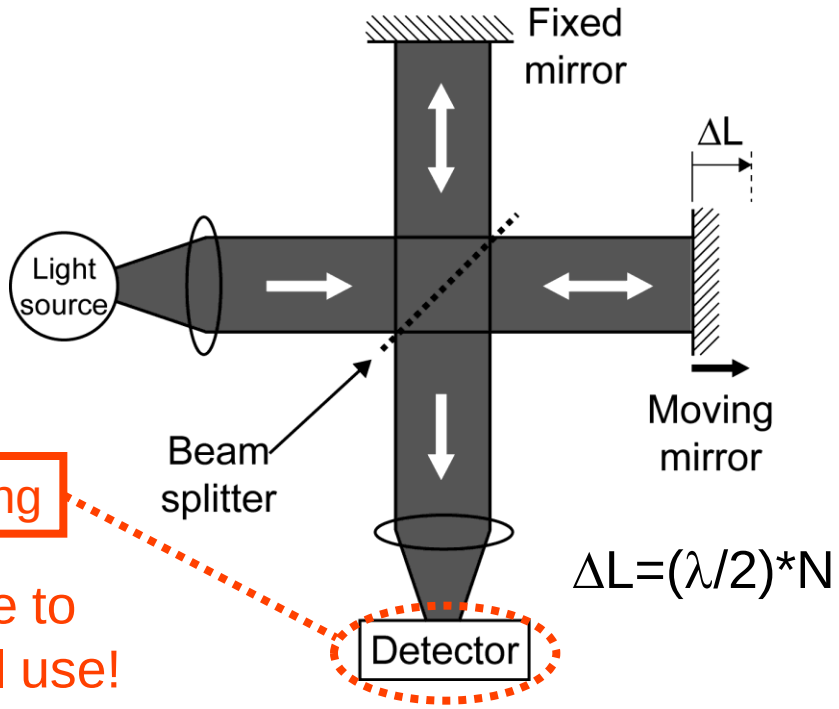
Electrical heterodyned method



Cryogenic cooling

Obstacle to practical use!

Optical interferometric method



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

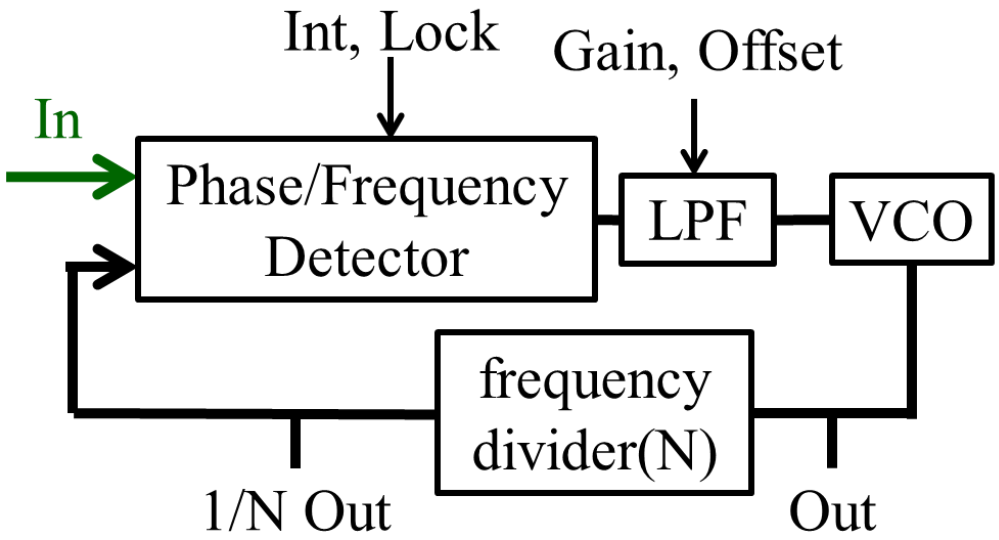
→Requirement of new method optimized for THz wave!

Tracking Oscillator

位相同期により入力信号を増幅

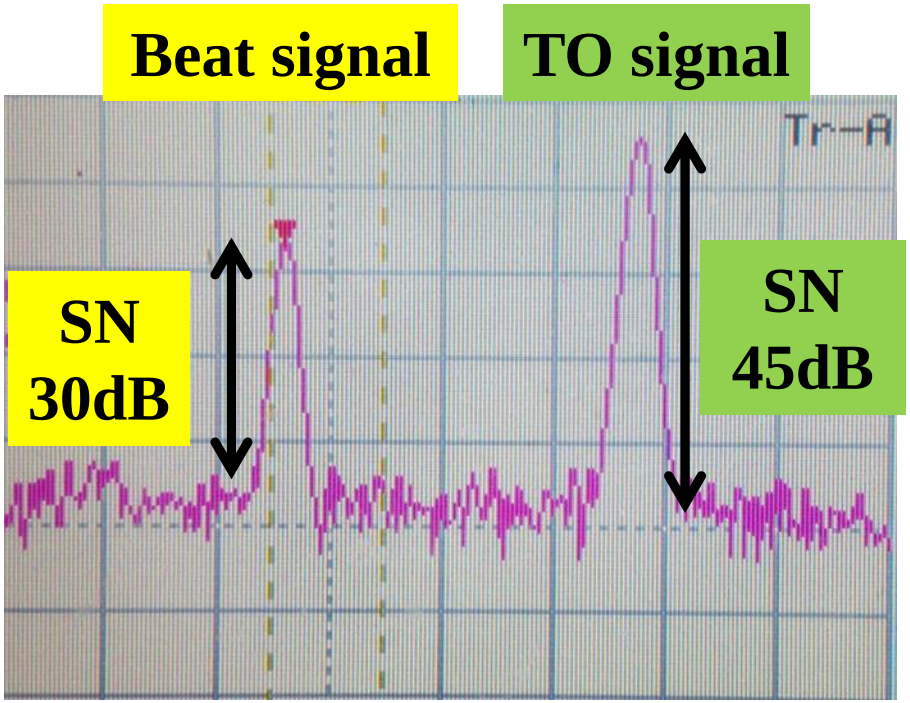
入力周波数の変動はVCOがトラッキングし，位相同期を維持

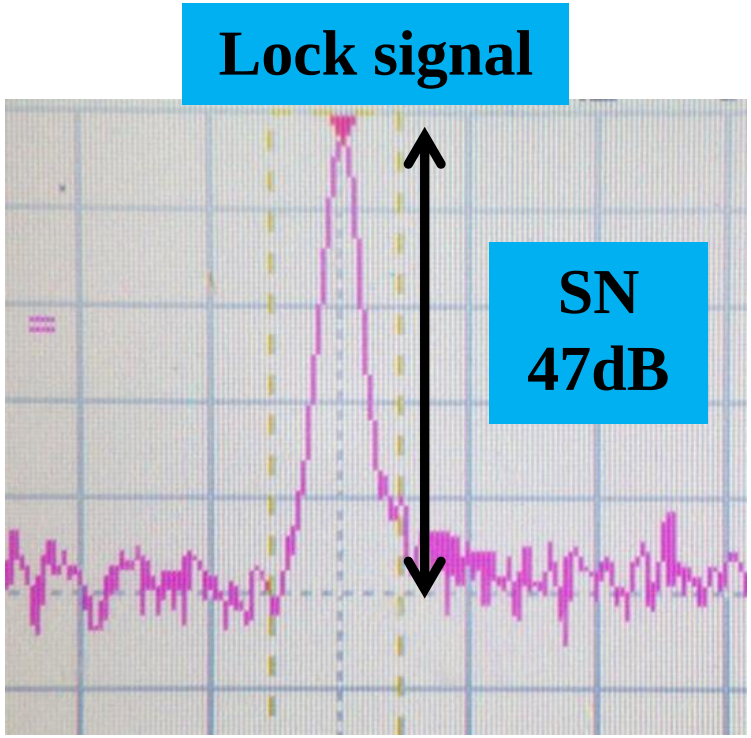
SN比の向上



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

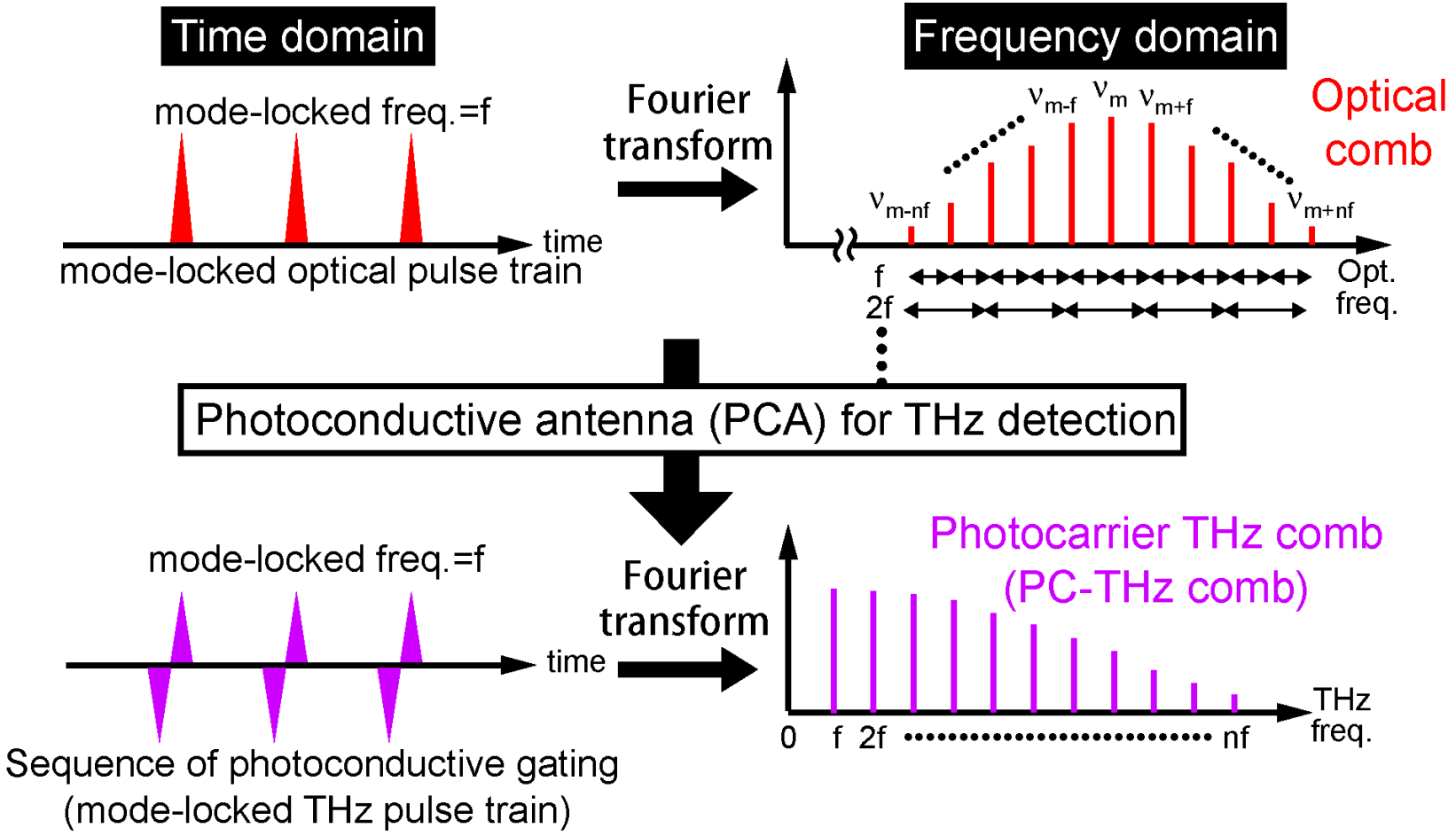
Tracking Oscillator の特性評価





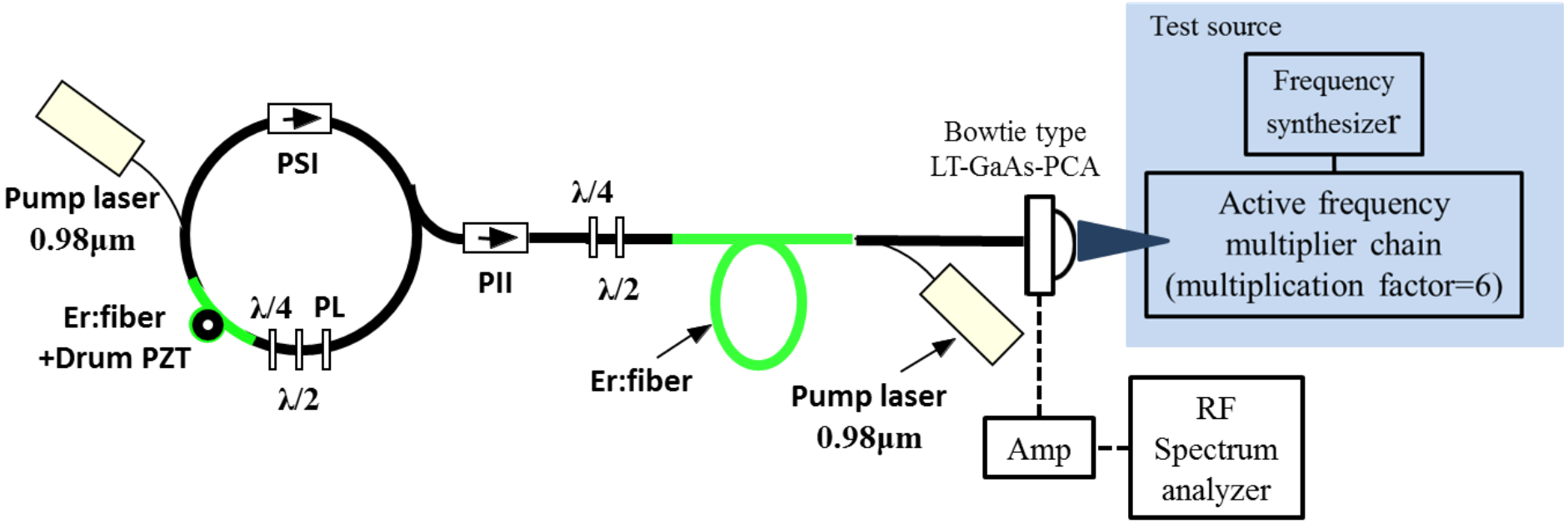
最低30dB (RBW10kHz) のビート信号においてトラッキングオシレーターでロック可能

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