27B1-5

Real-Time Absolute Frequency Measurement of CW-THz Radiation Based on a Free-Running THz Comb

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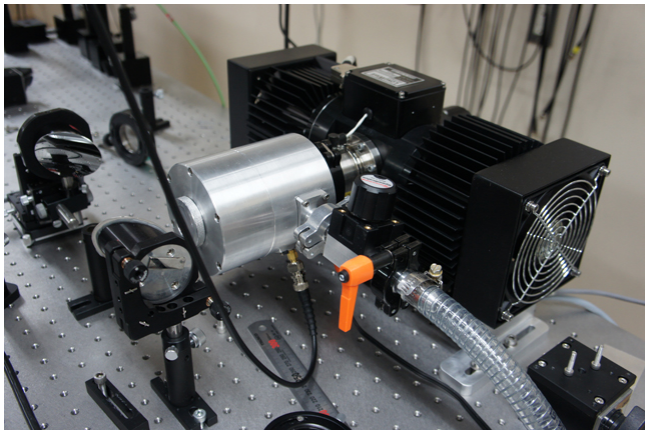
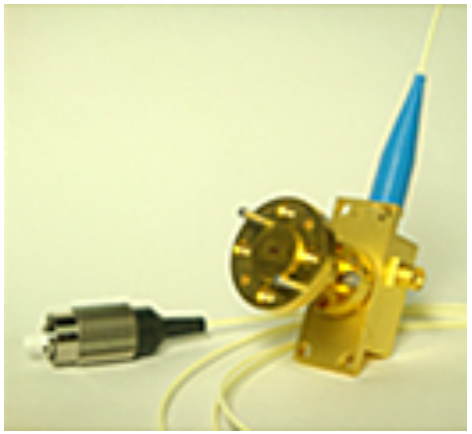
CLEO-PR 2015 in Busan

Background

Recent progress in CW-THz sources



THz-QCL



UTC-PD

The requirements of Frequency measurement have increased

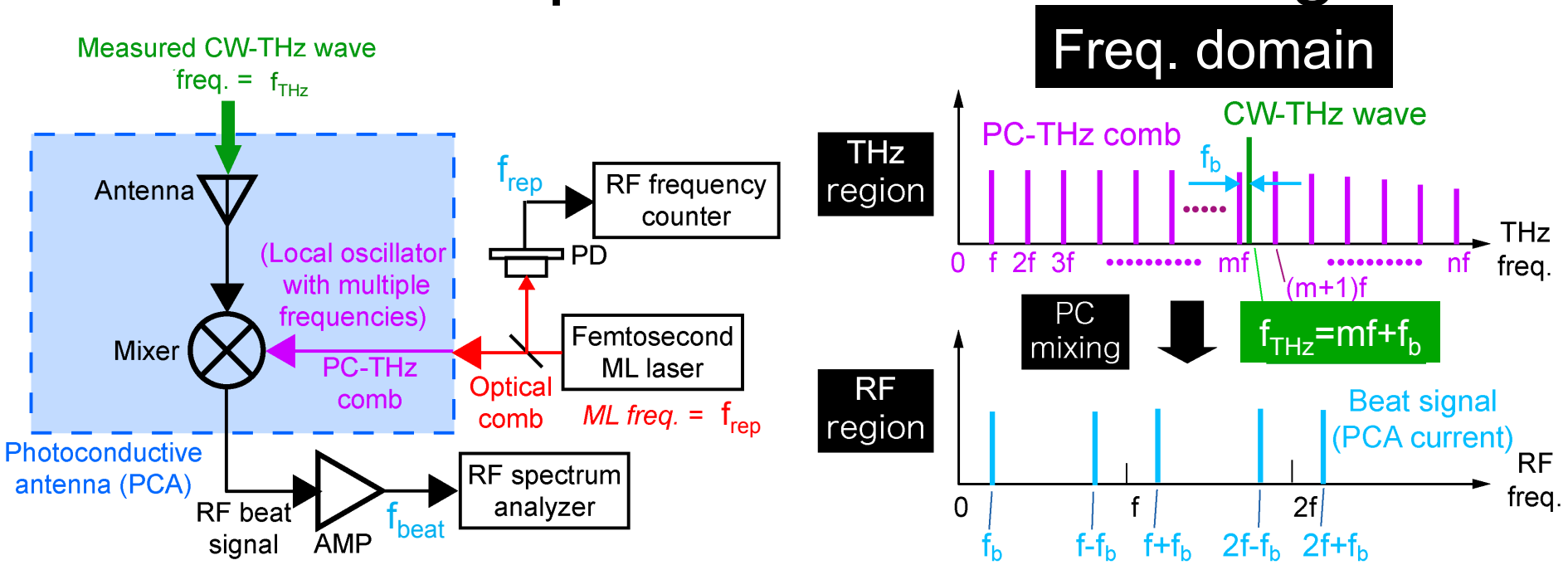
Conventional methods of the frequency measurement

- Electrical heterodyne method
- Optical interferometric method

Cryogenic cooling of mixers or detectors is required

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

THz-comb-referenced frequency measurement based on photoconductive mixing



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

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

Ref)
*Opt. Express **16**, 13052 (2008); Stabilized Ti:S laser, precision=10^{-11}, not real-time*
*Opt. Express **17**, 17034 (2009); Stabilized Er:fiber laser, precision=10^{-11}, not real-time*
*Opt. Express **23**, 11367 (2015); Stabilized dual Er:fiber laser, precision=10^{-11}, real-time*

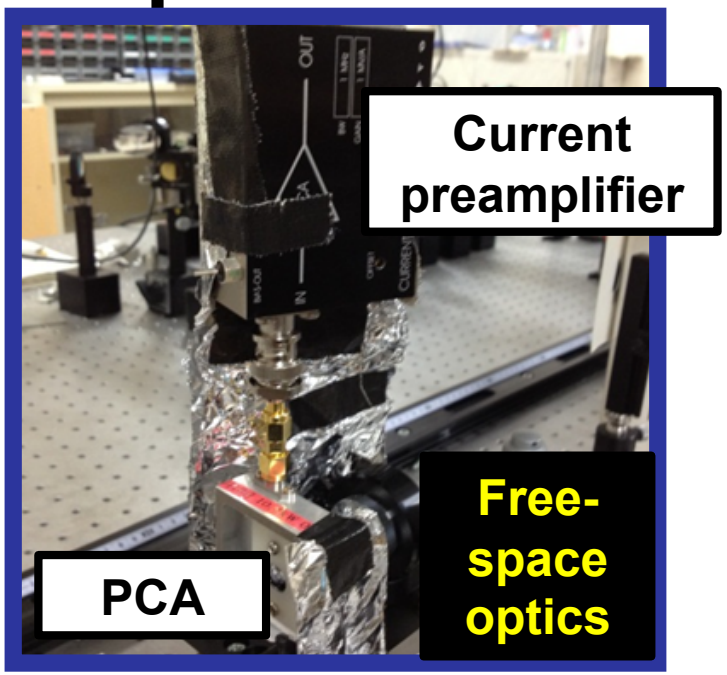
Problems of previous studies for practical use

(1) Probing head using free-space optics and external current preamplifier

✔Bulky and complicated!

(2) Precisely stabilized femtosecond ML laser

✔Expensive and delicate!



Probing head

Present talk

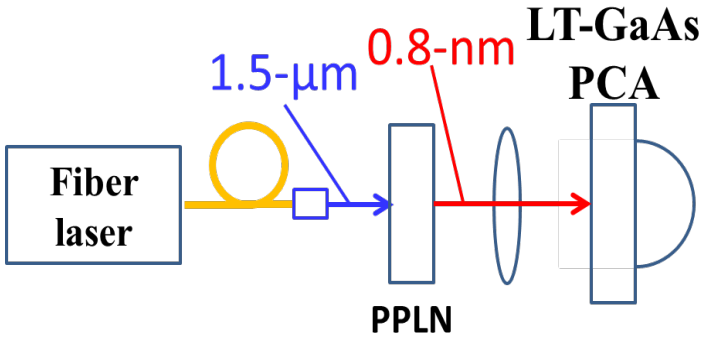
(1) Compact and robust probing head using fiber optics and AMP-IC-integrated PCA

(2) Real-time, absolute frequency measurement using a free-running laser

(1) Compact and robust probing head using fiber optics and AMP-IC-integrated PCA module

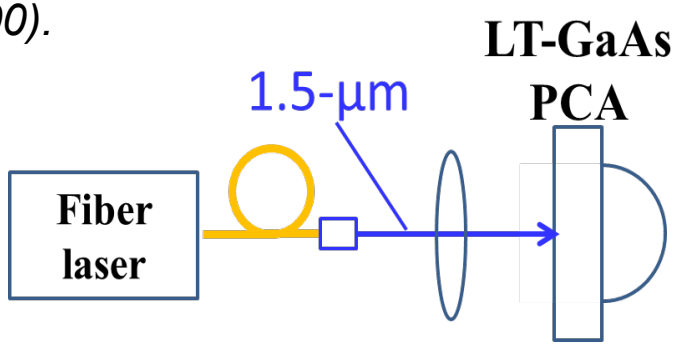
Direct excitation of LT-GaAs PCA by 1.5-μm light

LT-GaAs-PCA@0.8μm

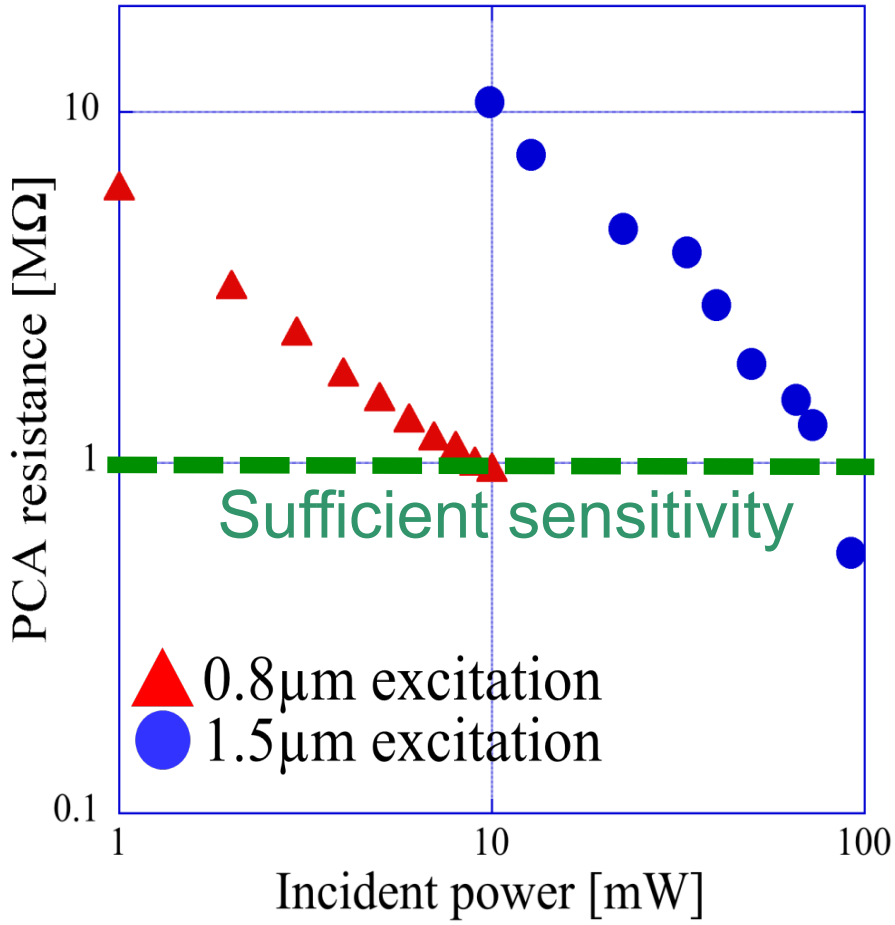


LT-GaAs-PCA@1.5μm

Ref) M.Tani et al, Appl. Phys. Lett. ***77****, 1396 (2000).*



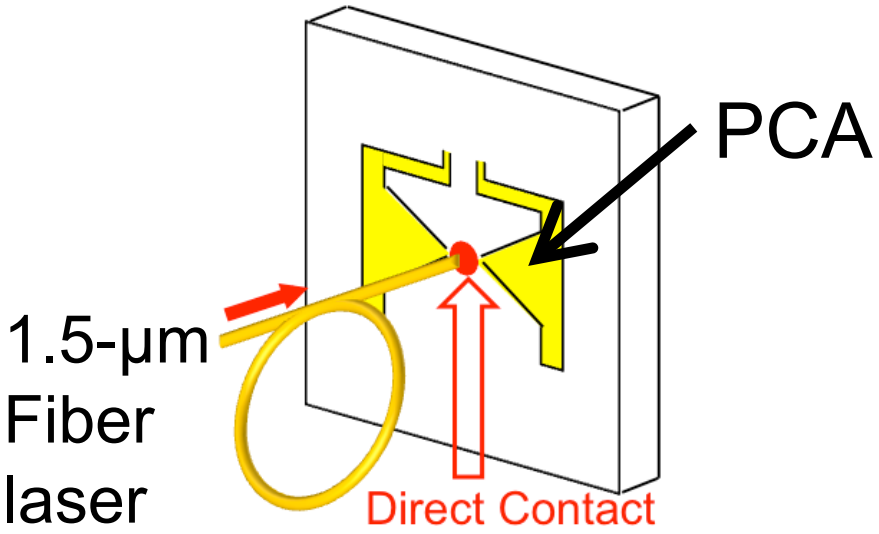
Dependence of PCA resistance

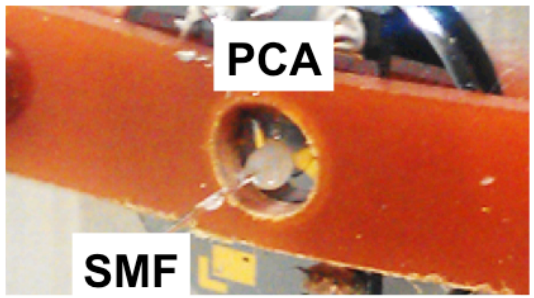


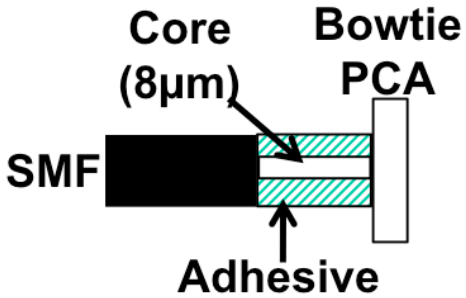
Considering SHG conversion efficiency(～10%), sensitivity at 1.5μm excitation is comparable to that at 0.8μm.

Compact and robust probing head

Lens-less coupling of 1.5-μm fiber laser output on PCA

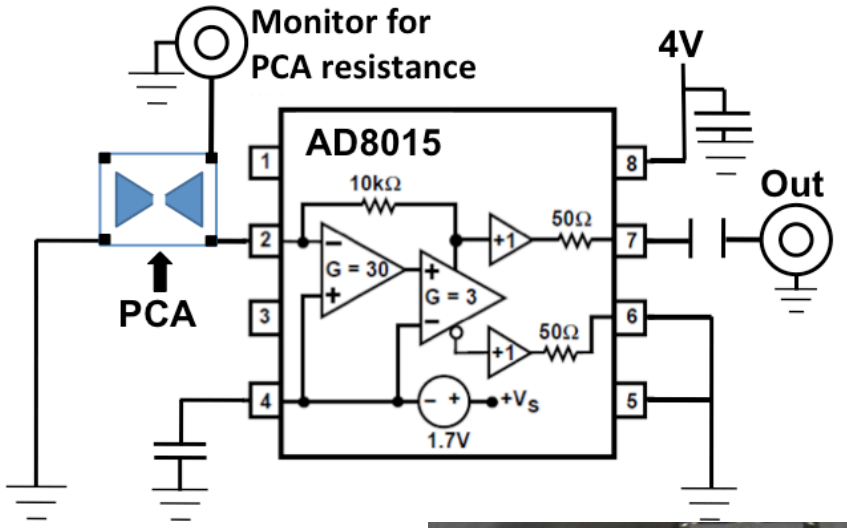




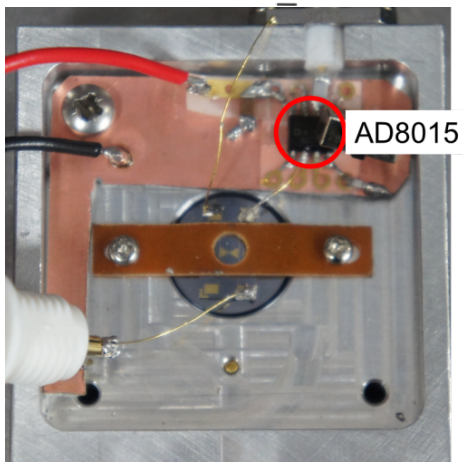


Lensless coupling

Integration of current preamp. IC with PCA

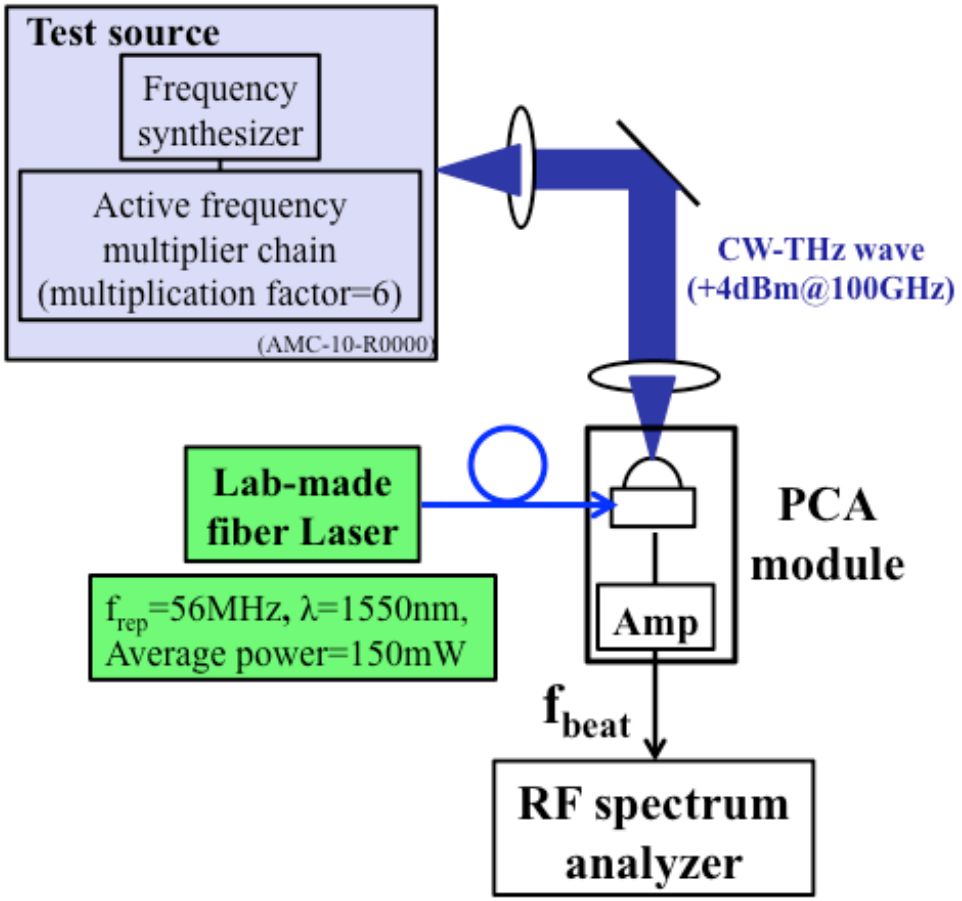


AD8015
Gain=10kV/A
BW=240MHz

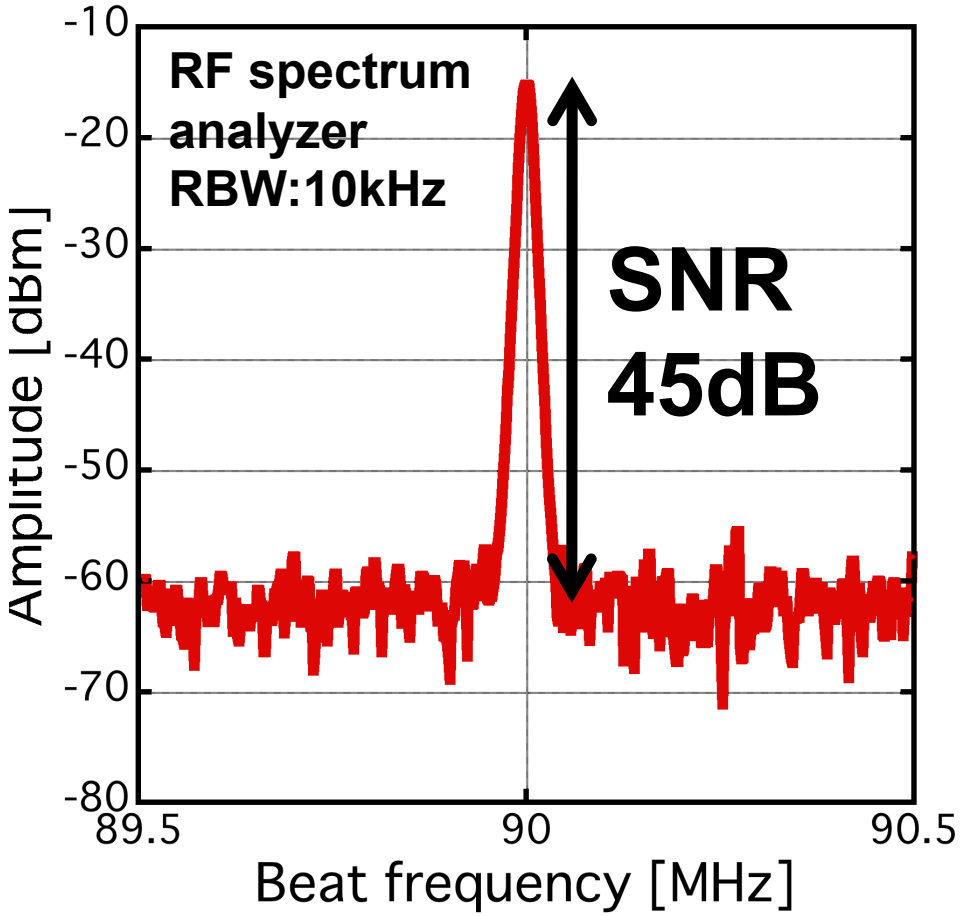


Result

Experimental setup



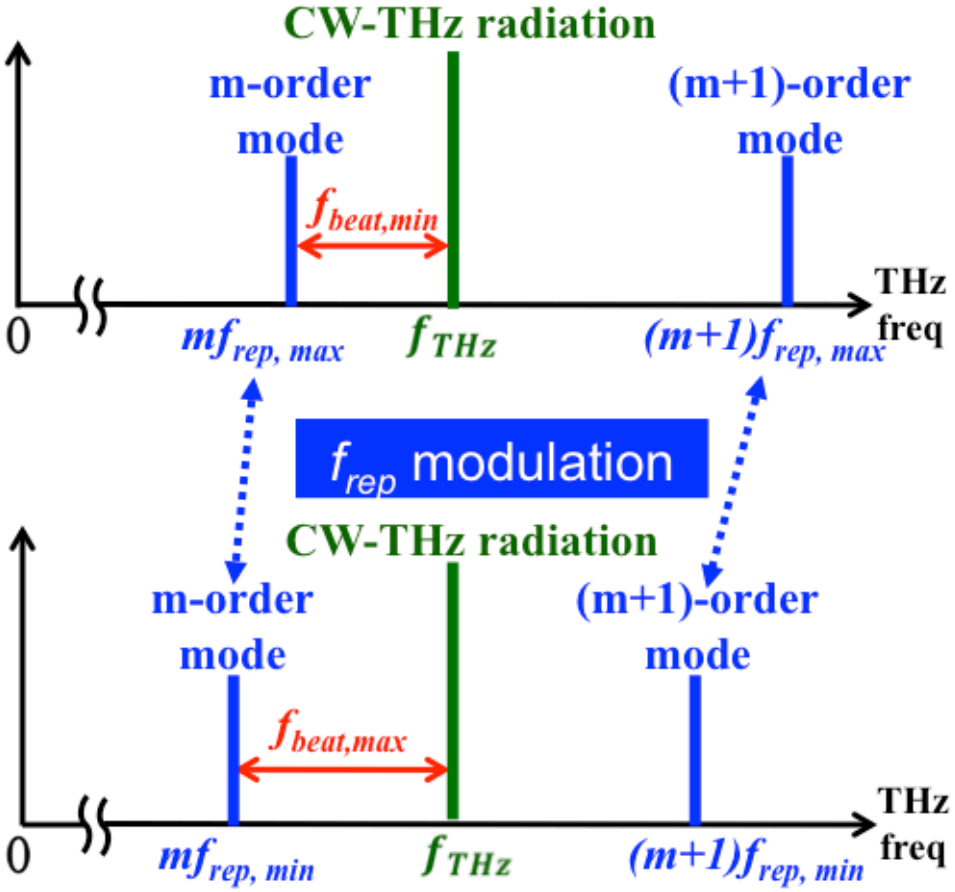
Beat signal between CW-THz wave and PC-THz comb mode



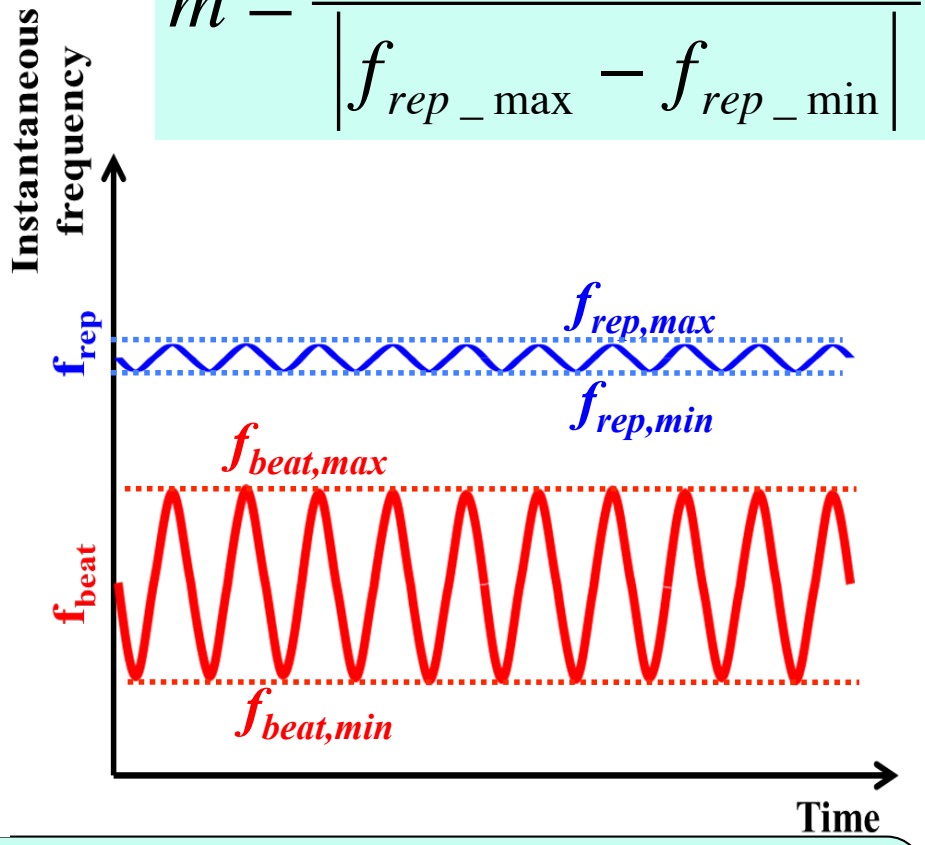
Beat signal SNR＞10dB (required for frequency measurement)

(2) Real-time, absolute frequency measurement using a free-running laser

Real-time determination of CW-THz frequency using a f_{rep}-modulated PC-THz comb



$$m = \frac{\left| f_{beat\_\max} - f_{beat\_\min} \right|}{\left| f_{rep\_\max} - f_{rep\_\min} \right|}$$



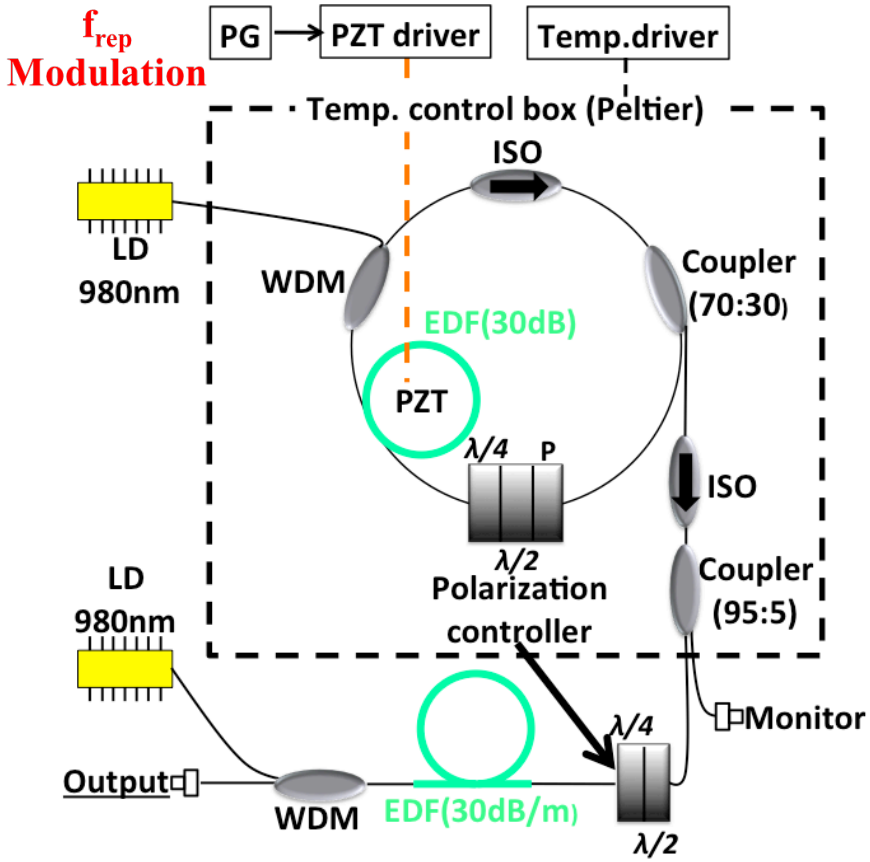
$f_{THz} = mf_{rep} - f_{beat}$ 〈in-pahse between f_{rep} and f_{beat}〉

$f_{THz} = mf_{rep} - f_{beat}$ 〈out-of-pahse between f_{rep} and f_{beat}〉

Portable f_{rep}-modulated Er:fiber laser

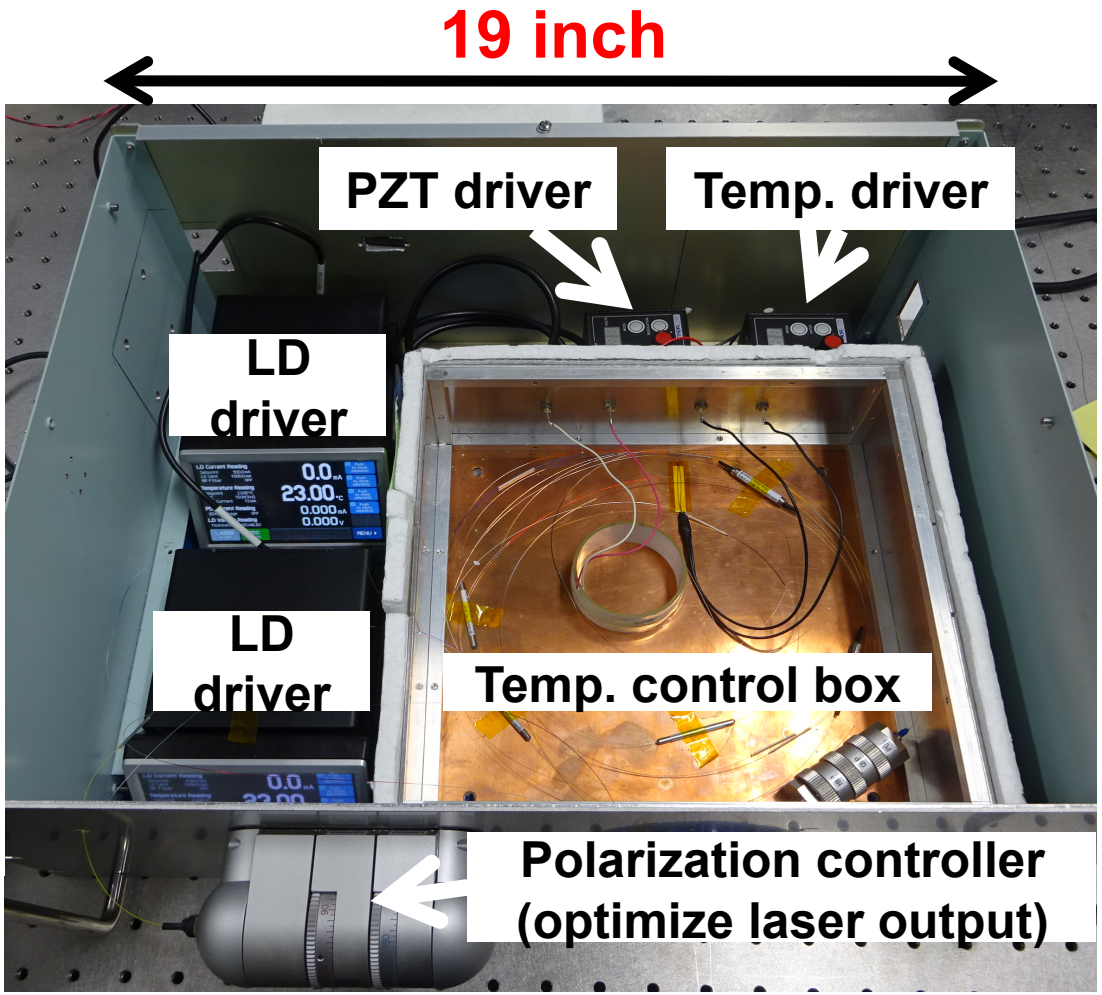
~compact, no stabilization, fiber output~

Cavity configuration

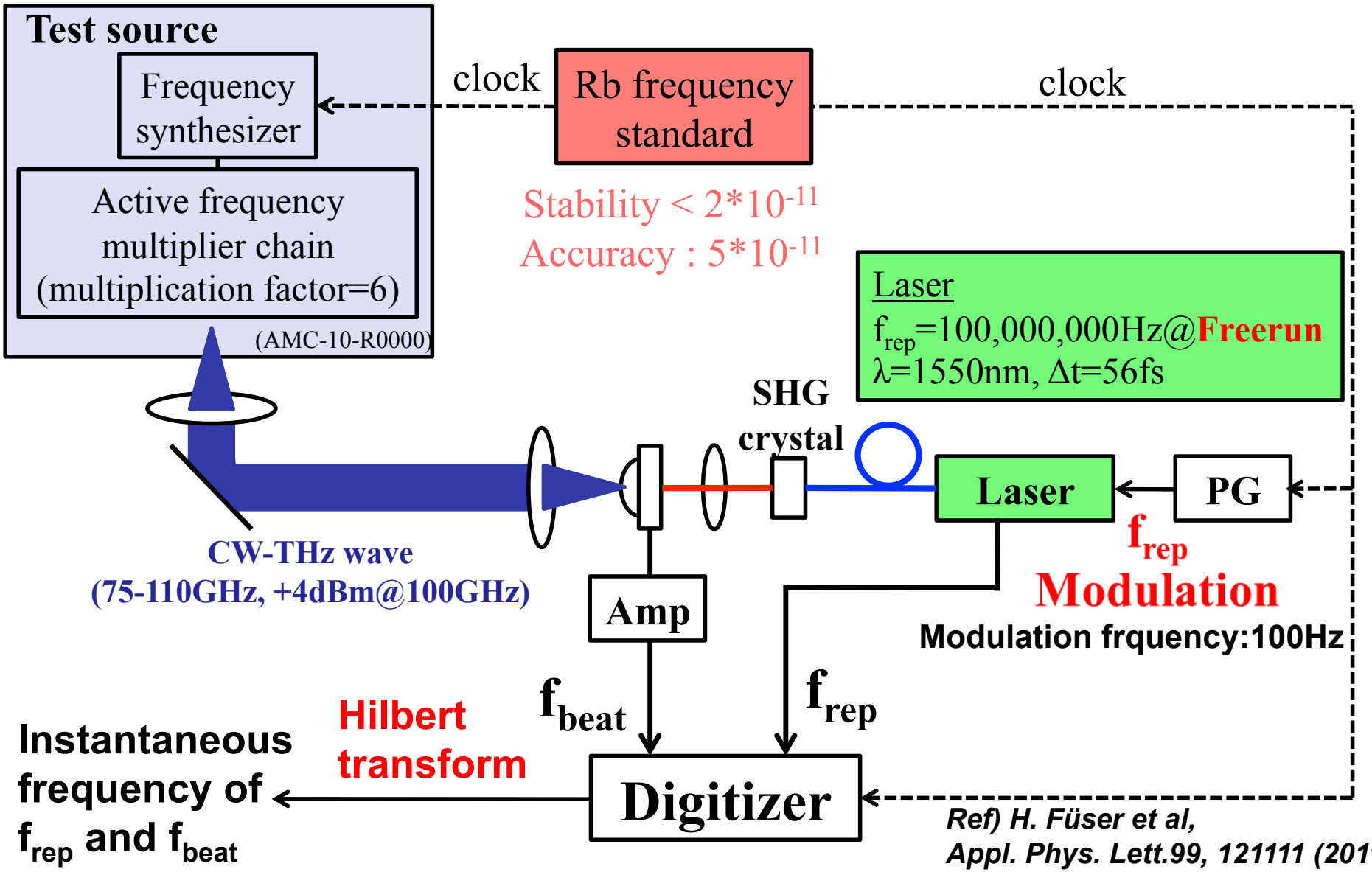


Center wavelength 1550nm
Average output power 110mW

Photograph



Experimental setup



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

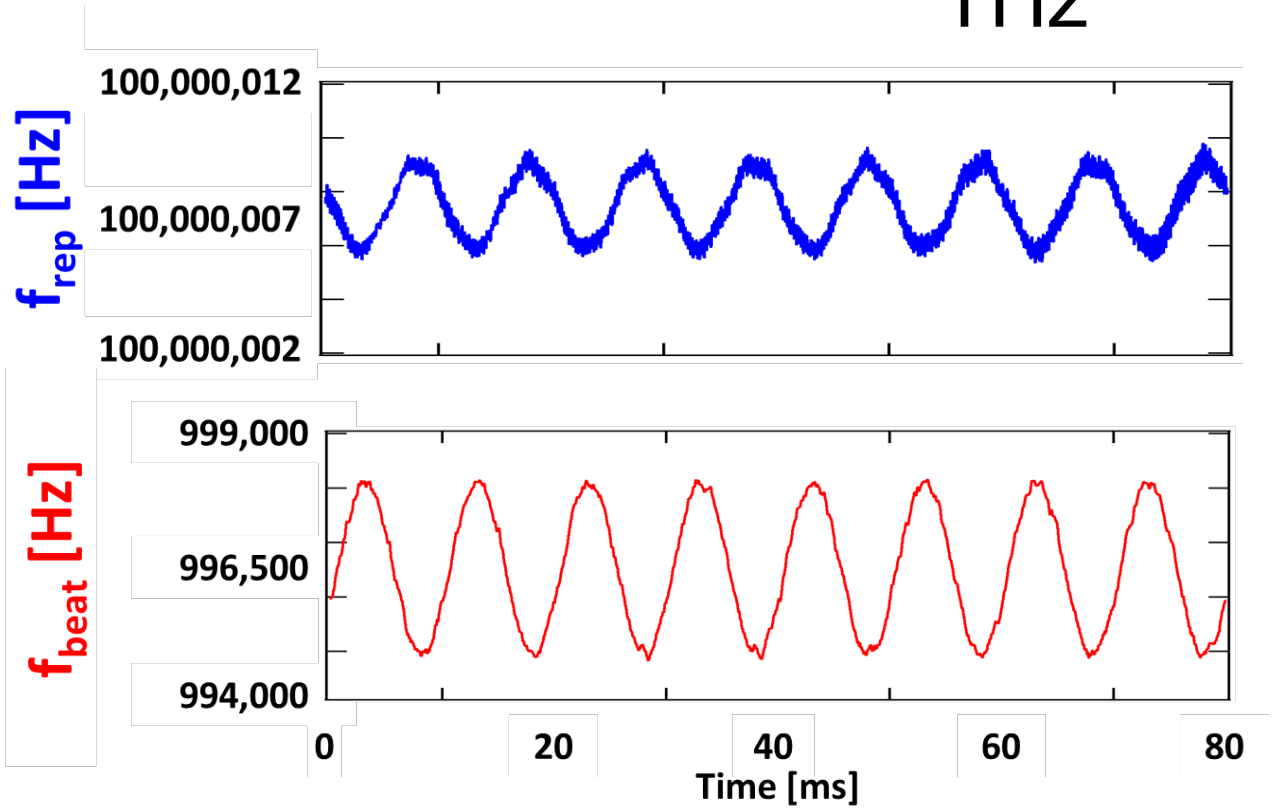
Real-time determination of f_{THz}

Sampling rate 10 MHz

Fitting of f_{rep} and f_{beat}
δf_{rep} = 3.1446 Hz
δf_{beat} = 3144.6 Hz

m = 1000

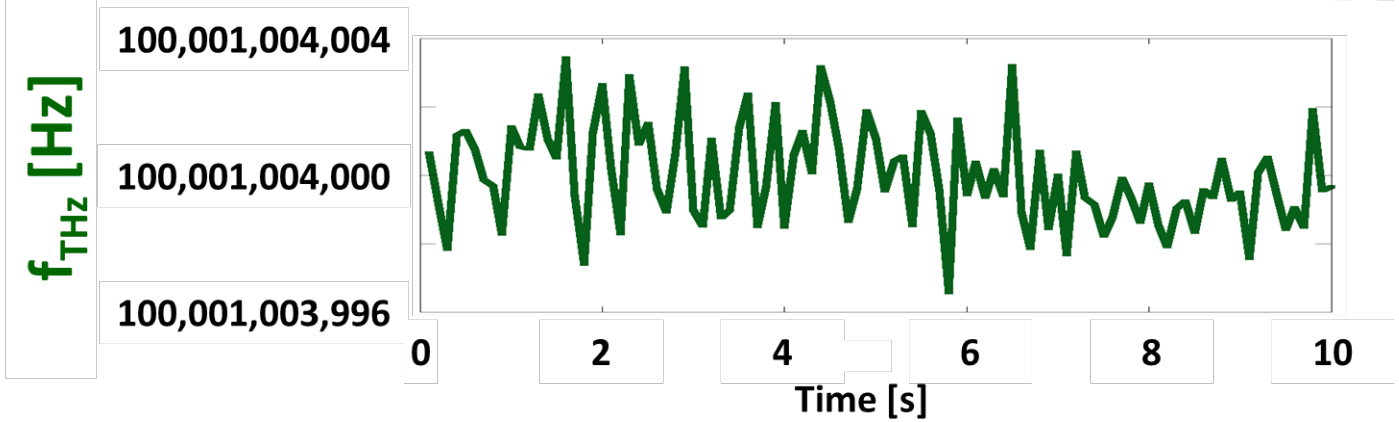
Data length 1 M



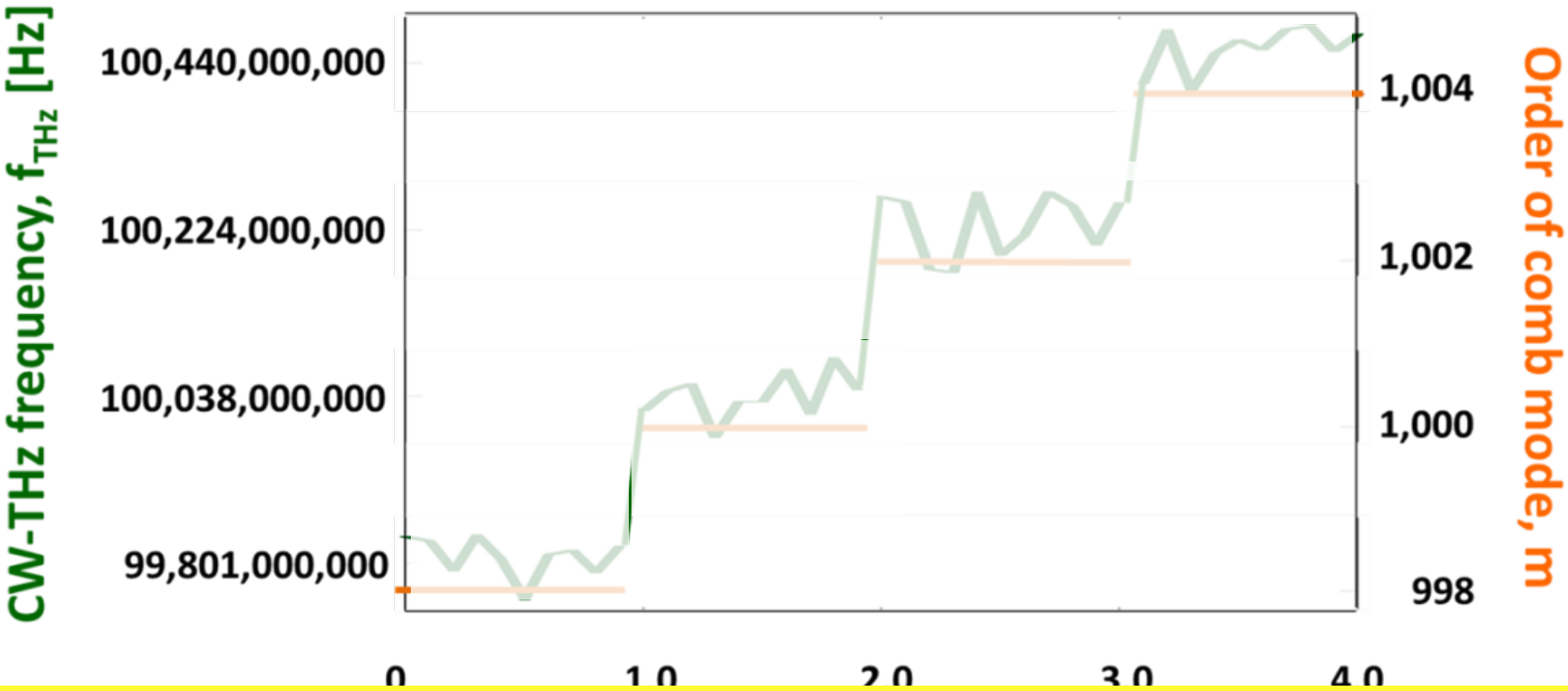
Sampling rate 10 Hz

Accuracy

6.2×10^{-12}



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

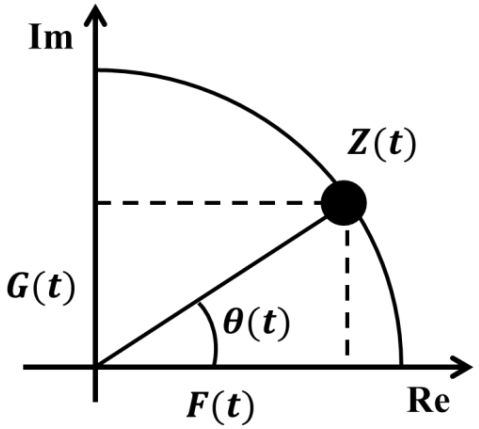


A high potential for real time monitoring of large fluctuation such as mode hopping in CW-THz sources!

Summary

- Compact and robust probing head based on lens-less coupling of fiber output and AMP IC-integrated PCA
- Portable, f_{rep}-modulated fiber laser
- Real-time, absolute frequency determination of CW-THz radiation at precision of 6.2×10^{-12}
- Applicable for large frequency change such as mode hopping

Instantaneous frequency measurement using Hilbert transformation

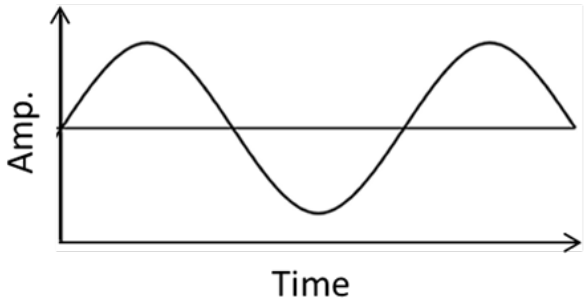


Ref) H. Füser et al, Appl. Phys. Lett. ***99****, 121111 (2011).*

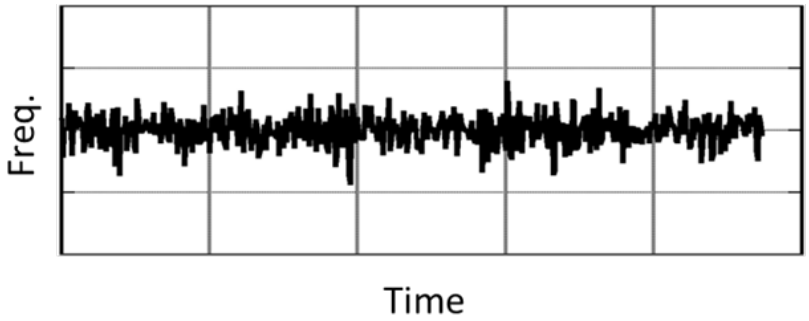
$$Z(t) = F(t) + iG(t)$$

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

$$\theta(t) = \arg[Z(t)] = \tan^{-1}\left[\frac{G(t)}{F(t)}\right] \qquad f = \frac{1}{2\pi} \times \frac{d\theta(t)}{dt}$$



Hilbert transform



Temporal waveform of f_{beat}

Instantaneous frequency of f_{beat}

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 determine by measuring Δf_{rep} and Δf_{beat} at the same time !!

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