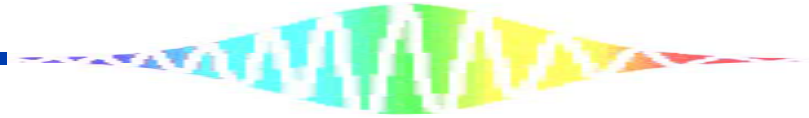


1. Introduction

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, UTC-PD, RTD, etc)

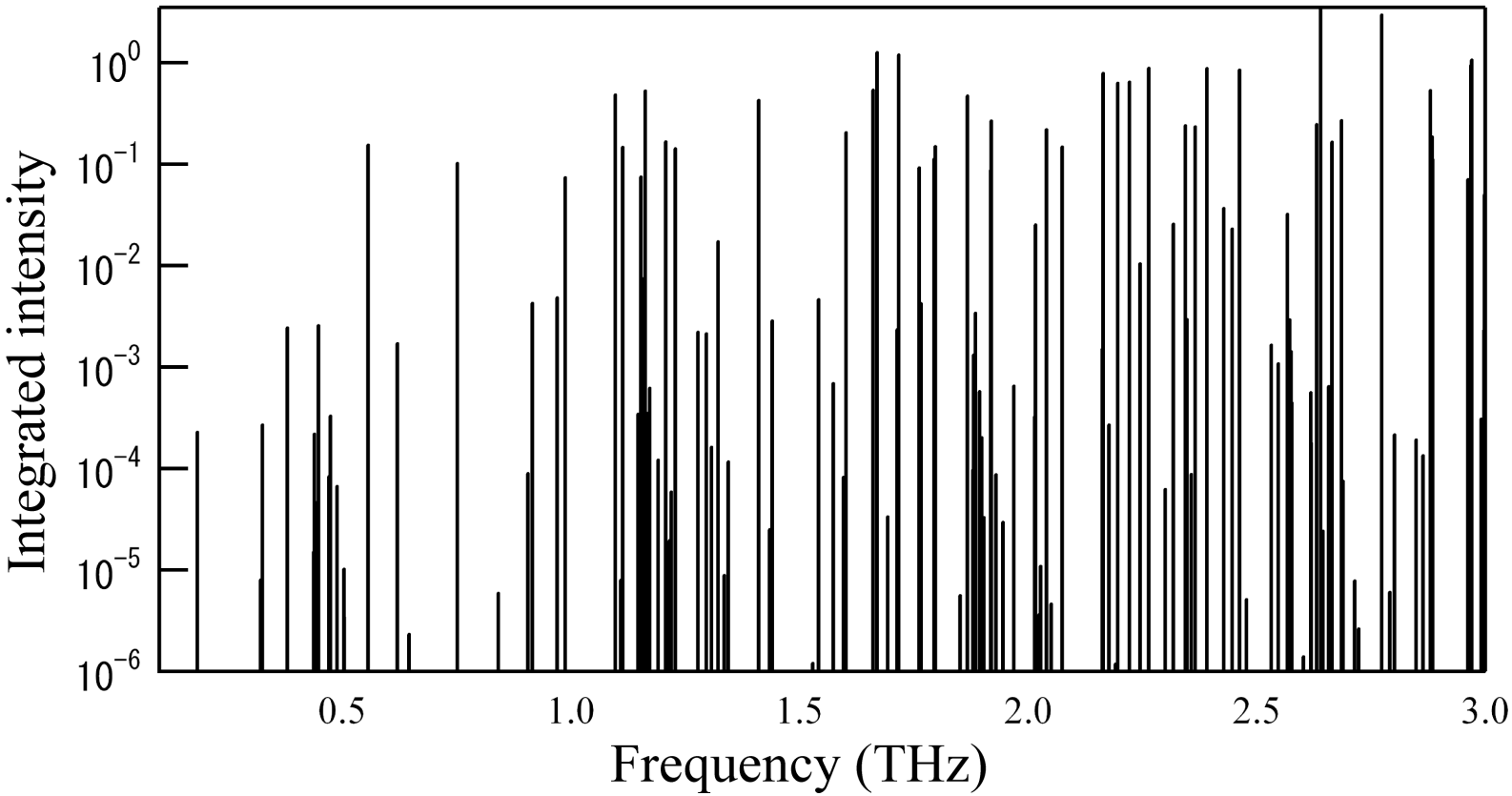
Precise frequency measurement of CW-THz wave is required!

However, techniques of frequency measurement in THz region have been underdeveloped yet.

Conventional method (1)

Frequency calibration based on water vapor absorption

ref) http://spec.jpl.nasa.gov/

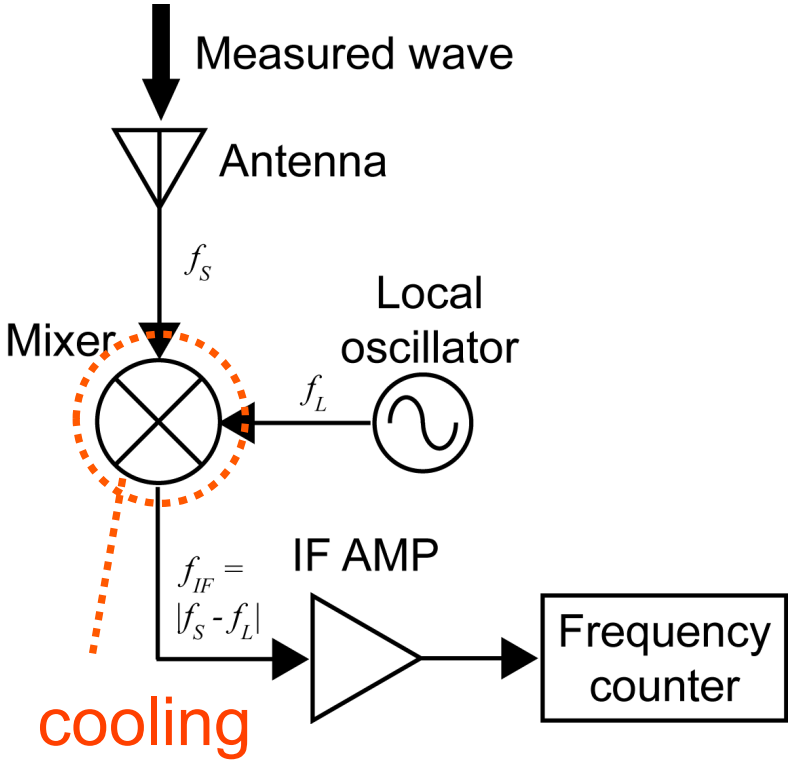


Simple

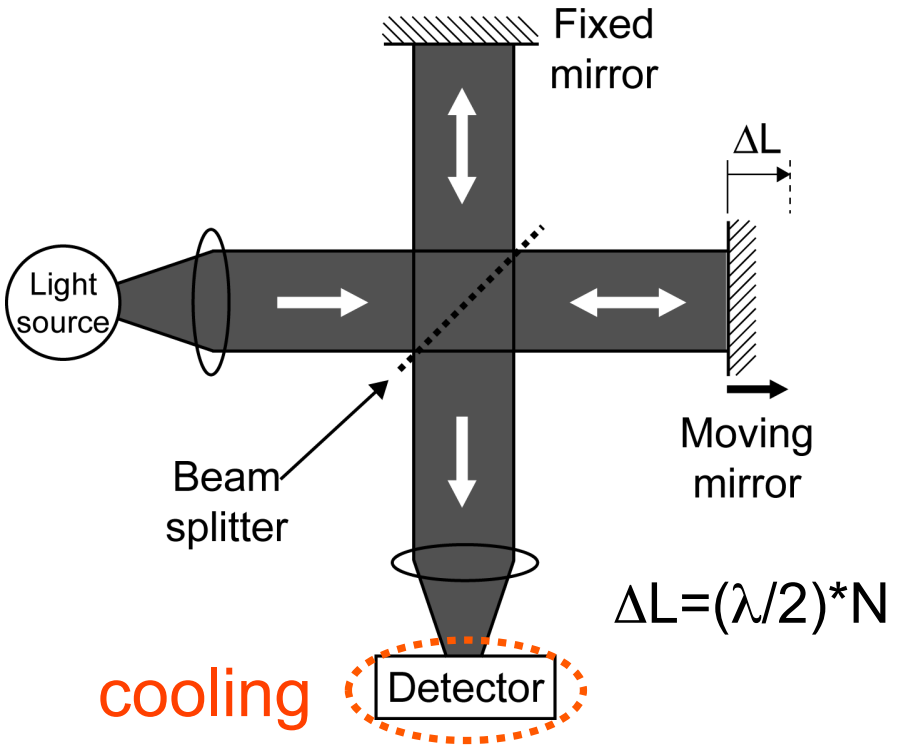
Pressure broadening of absorption line, discrete distribution

Conventional method (2)

Electrical heterodyned method



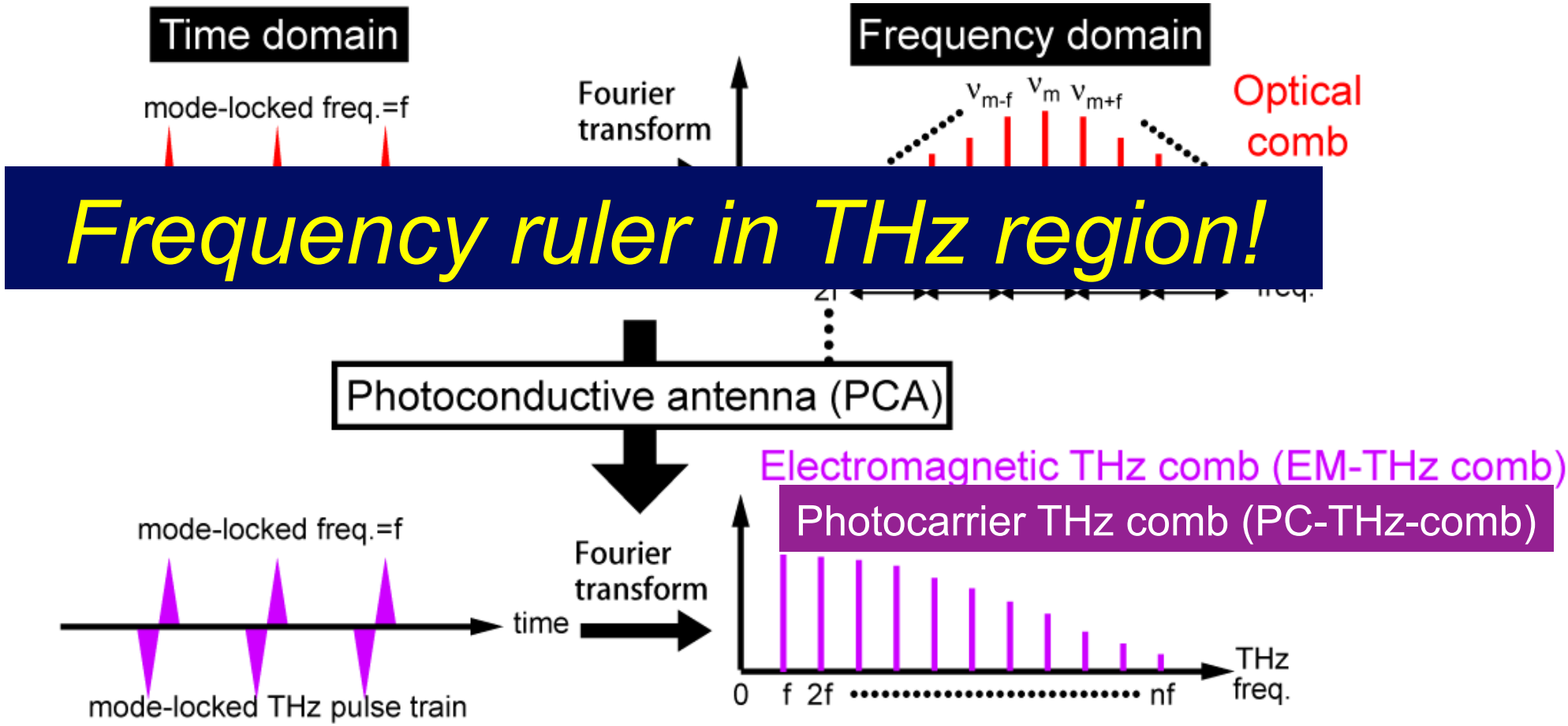
Optical interferometric method



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

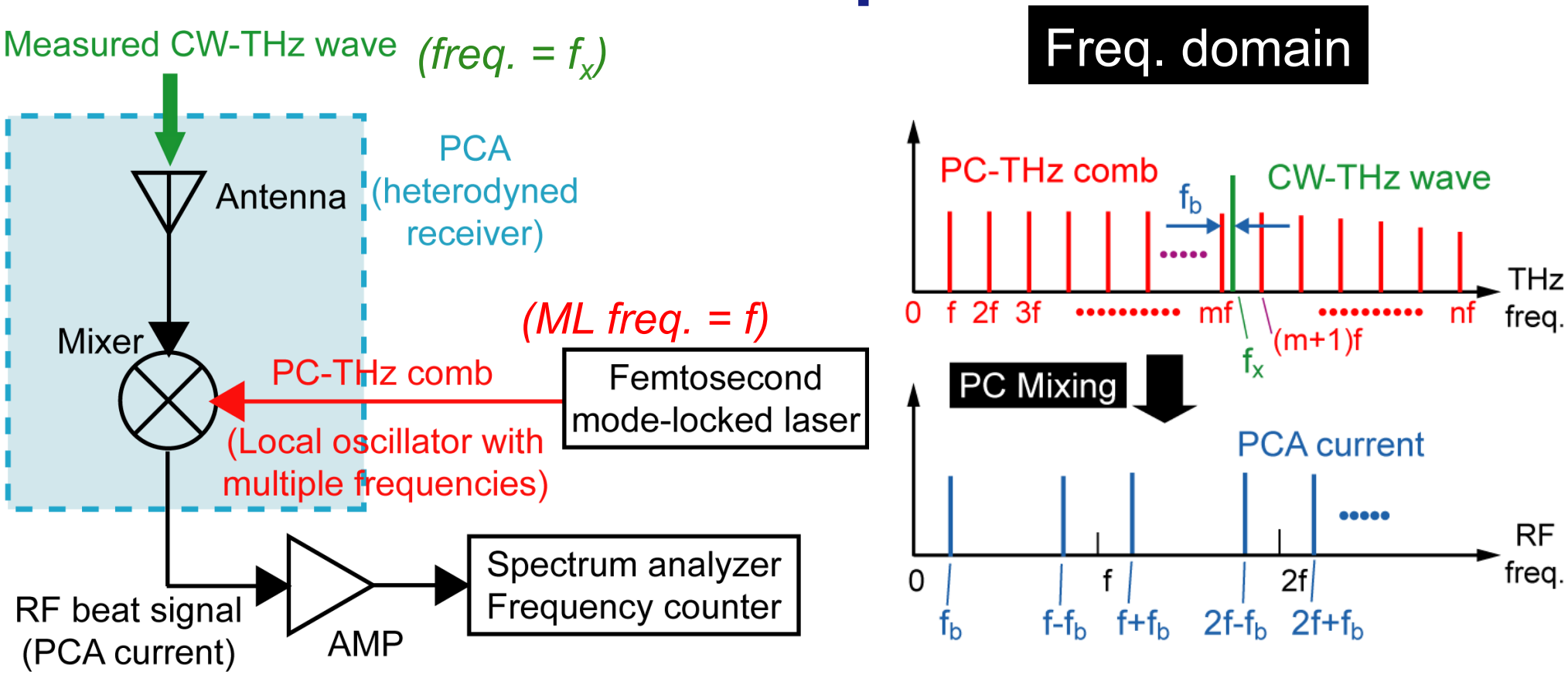
→Requirement of new method optimized for THz wave!

Optical comb and THz comb



Accurate, stable, broadband selectivity, high spectral purity, and absolute frequency calibration

Principle



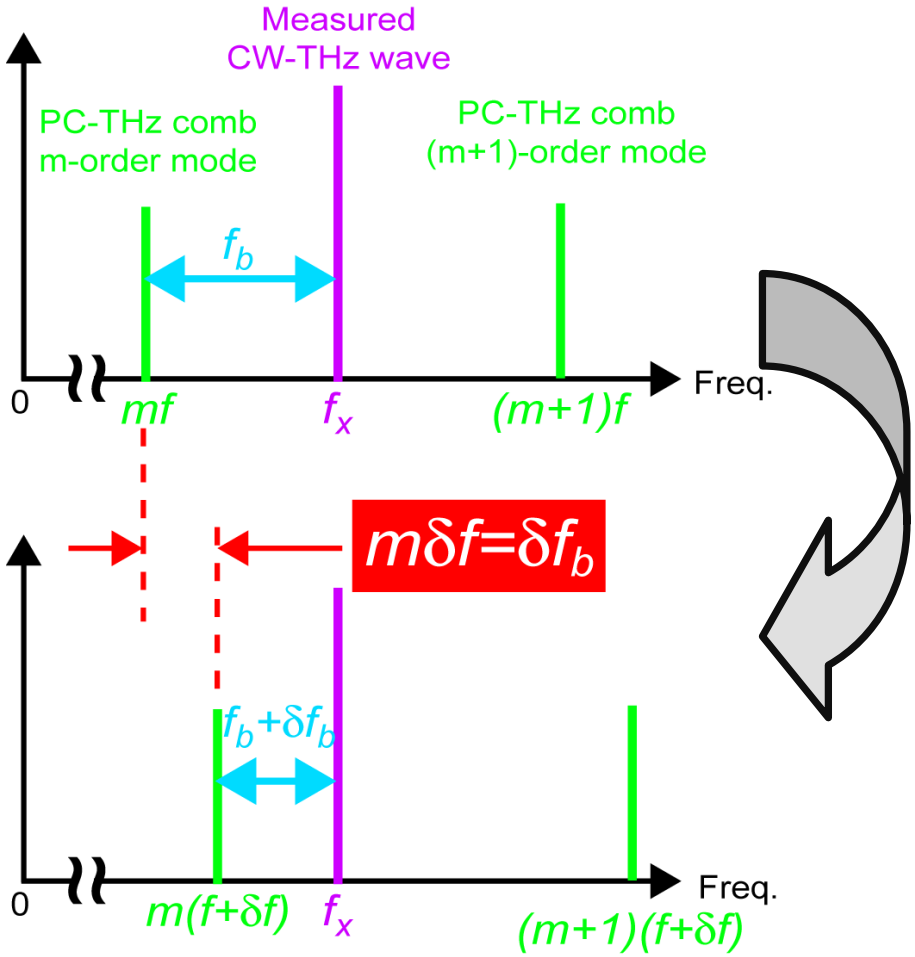
measure

$$f_b = \left| f_x - mf \right|$$

sign

m: order of comb mode
f: ML freq.
f_b: beat freq.

Determination of order of m



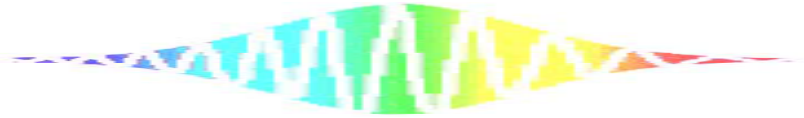
Shift of ML freq. by δf
(f ® f+δf)

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

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

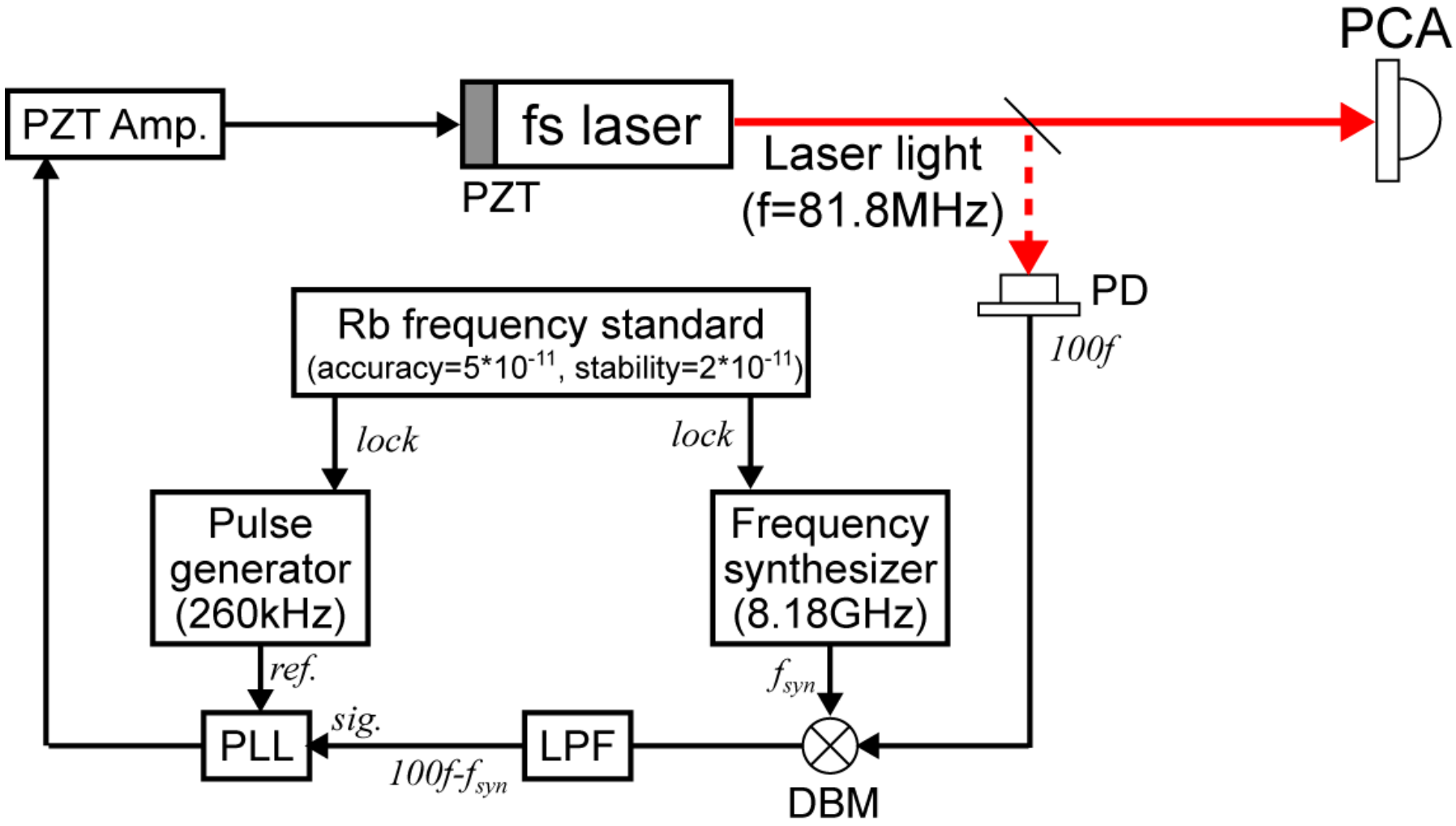
$$f_x = mf - f_b \qquad (\delta f_b/\delta f > 0)$$

$$f_x = mf + f_b \qquad (\delta f_b/\delta f < 0)$$

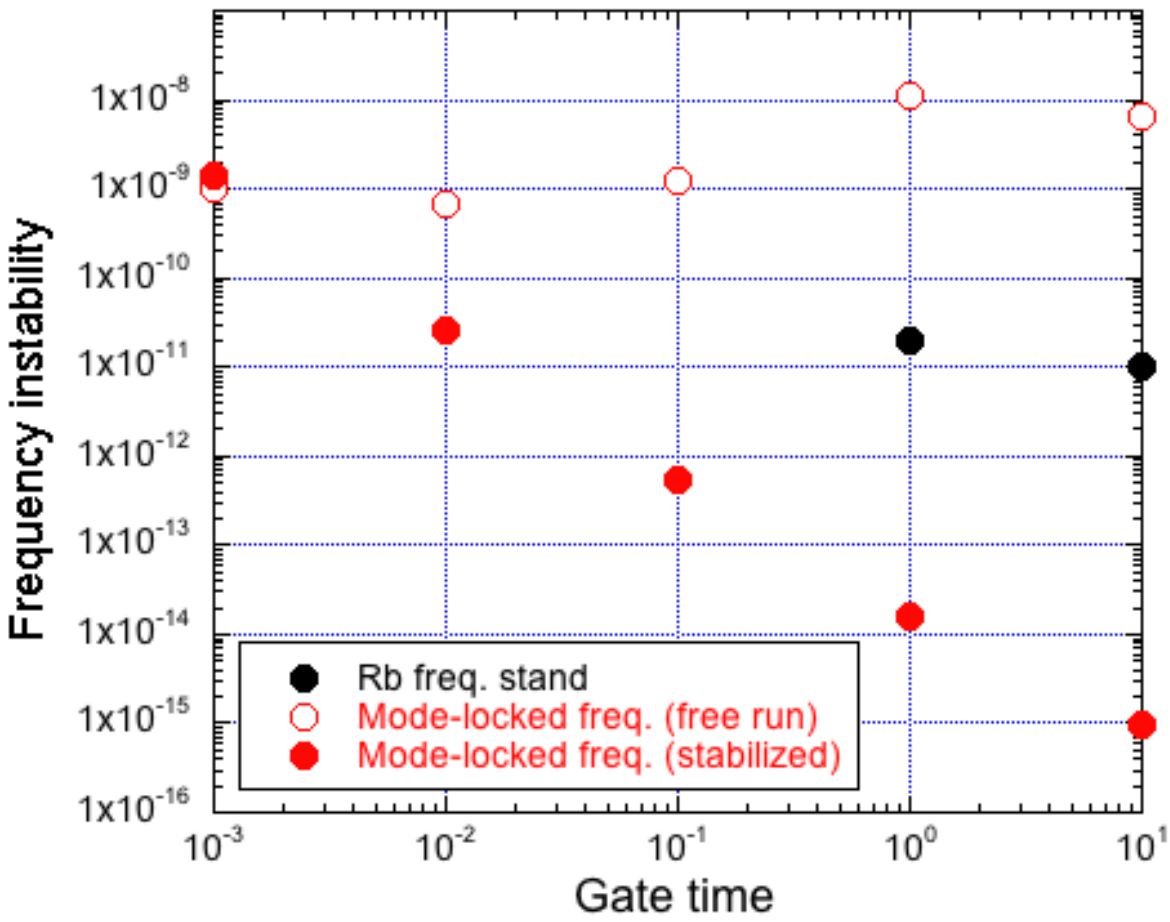


2. Ti:S-laser-based THz spectrum analyzer

Laser source for PC-THz comb

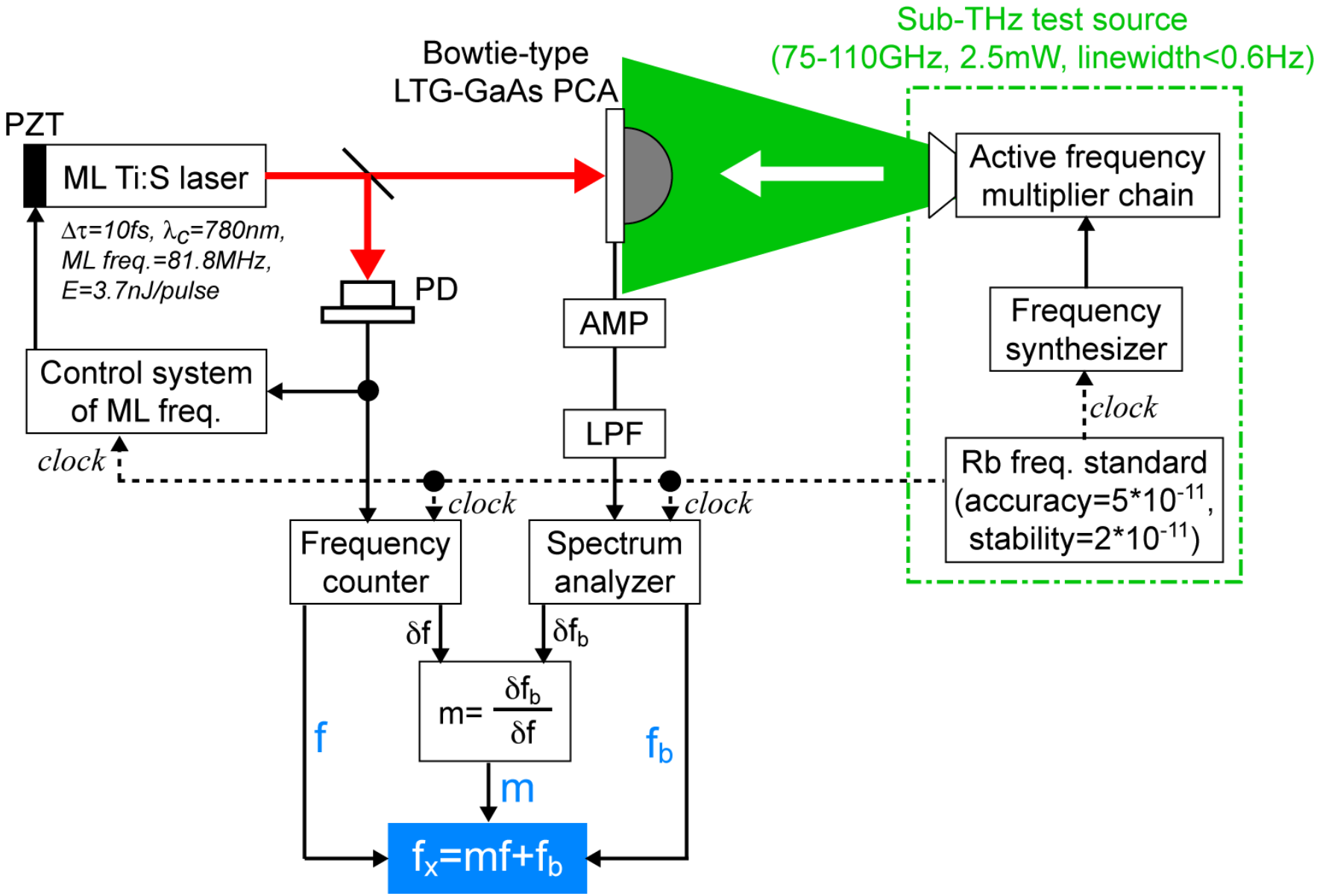


Stability of mode-locked frequency



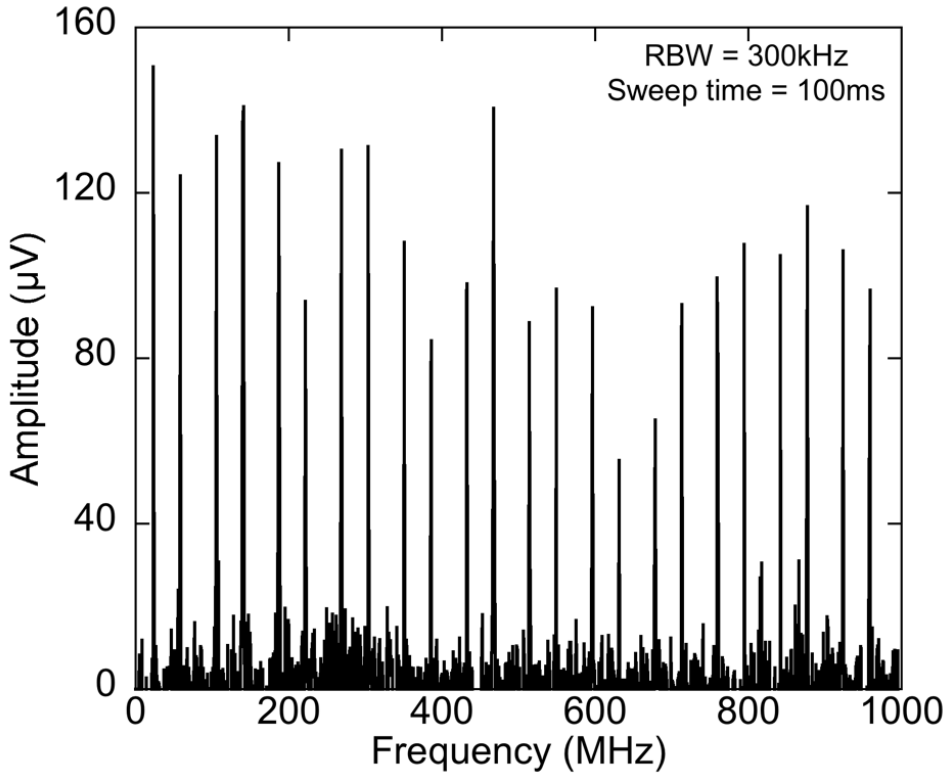
Stability and accuracy of PC-THz comb is equal to those of Rb freq. standard

Experimental setup

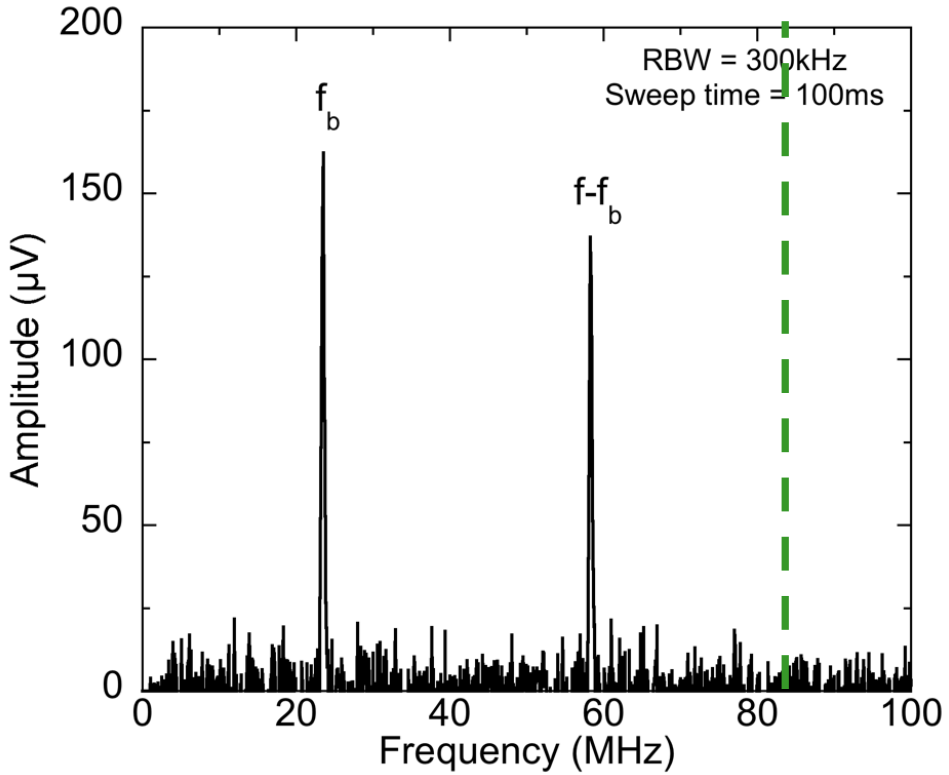


Observation of beat signal (1)

（90GHz freq. multiplier source）



f=81.6MHZ

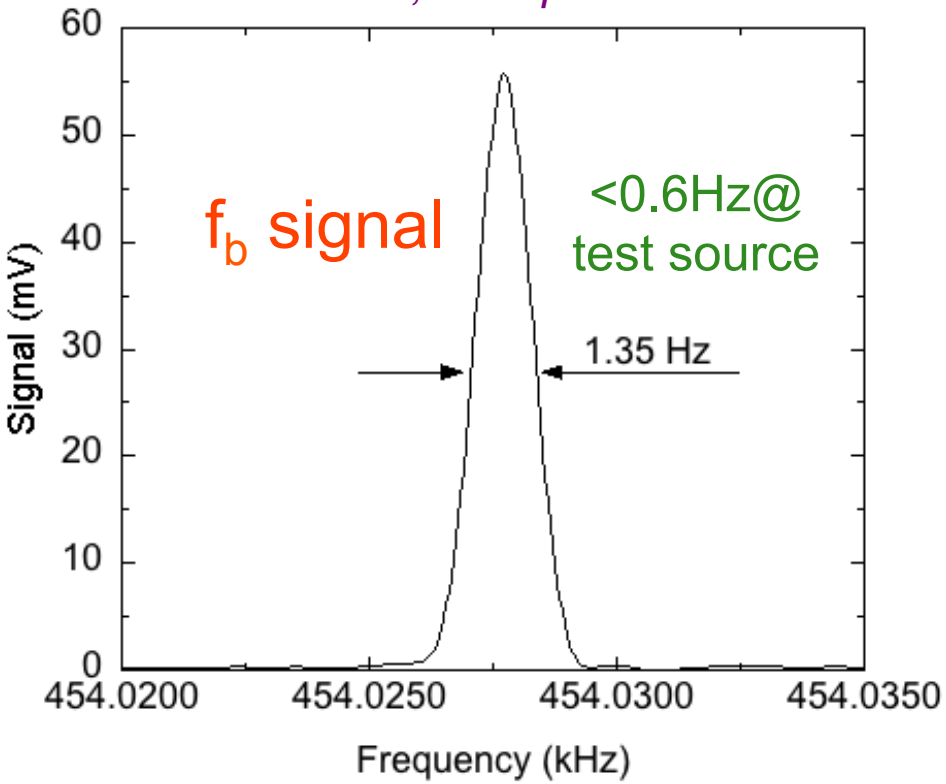


Observation of beat signal (2)

(90GHz freq. multiplier source)

Linewidth

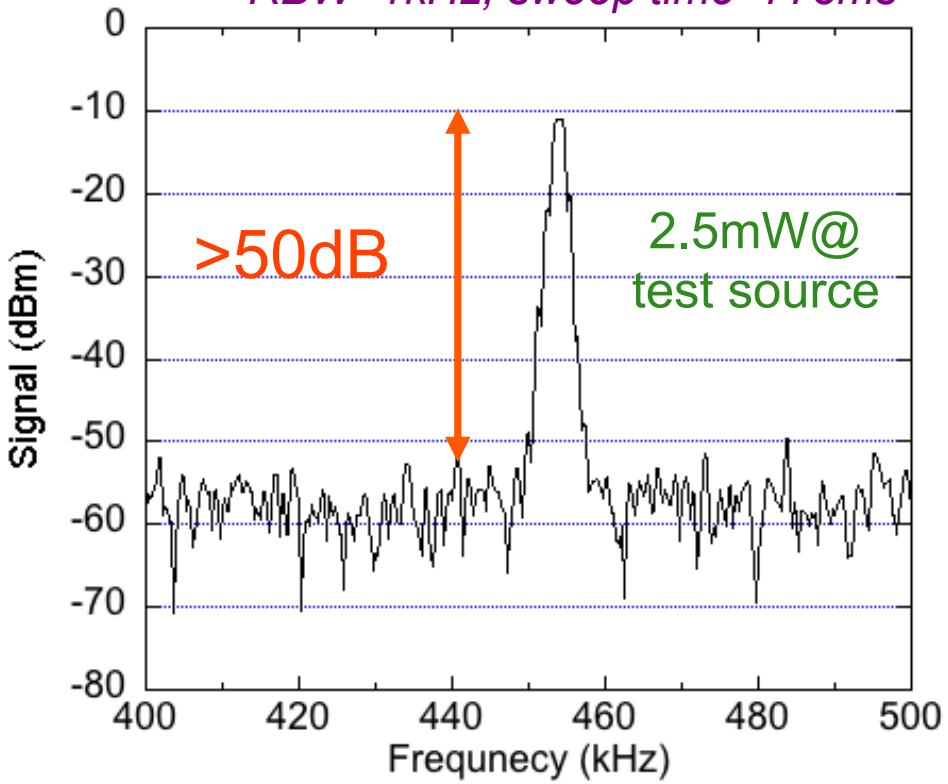
RBW=1Hz, sweep time=2.294s



Linewidth < 1Hz

Signal-to-noise ratio

RBW=1kHz, sweep time=773ms

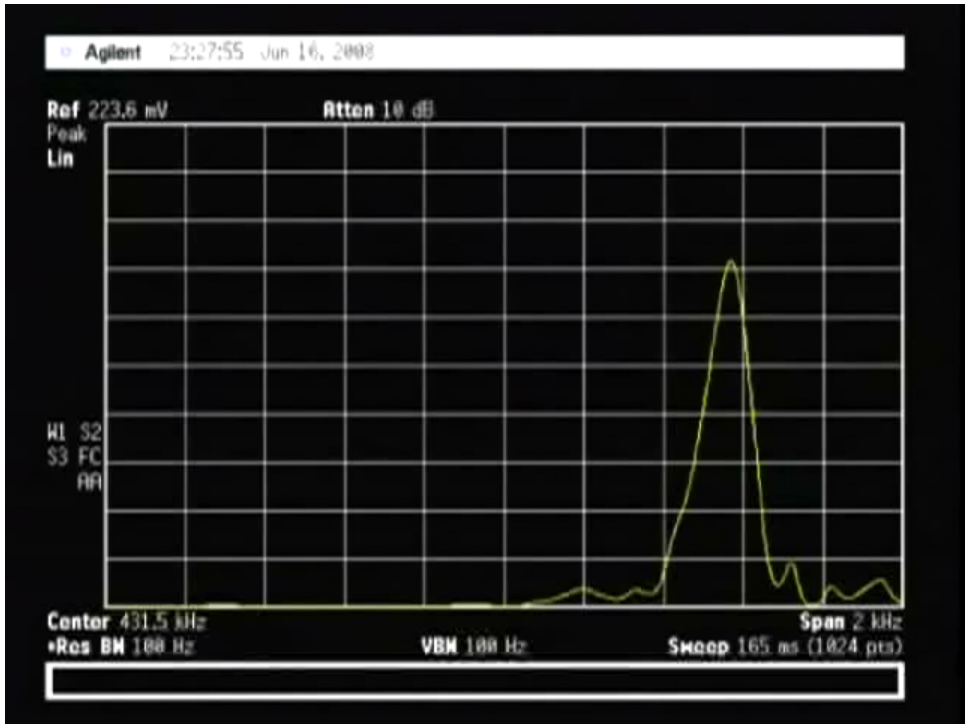


Detection limit = 25nW

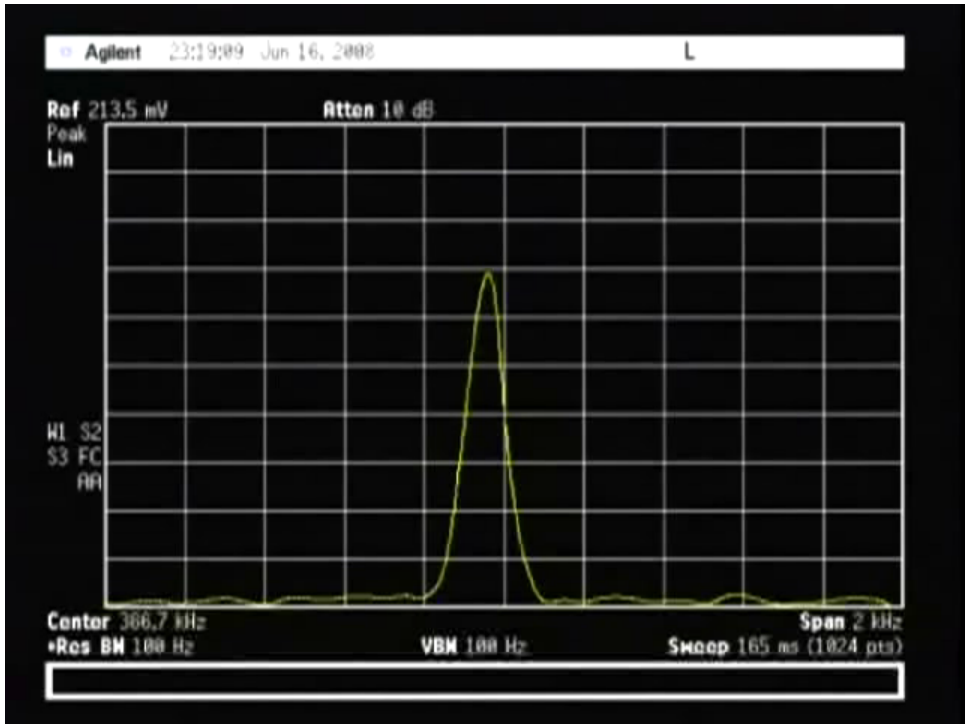
Observation of beat signal (3)

（90GHz freq. multiplier source）

Laser control : OFF



Laser control : ON

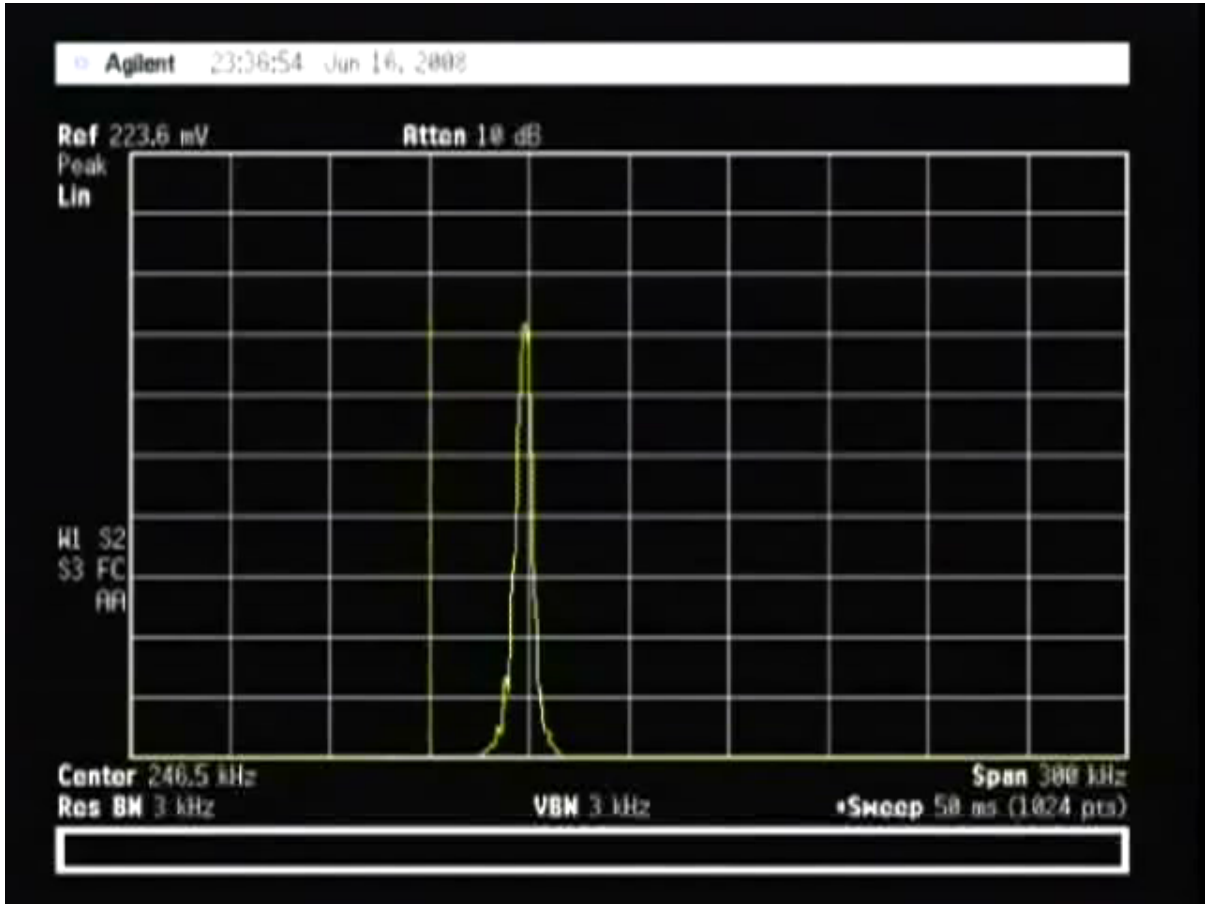


RBW=100Hz, sweep time=165ms, full span=2kHz

Observation of beat signal (4)

（freq. multiplier source wave）

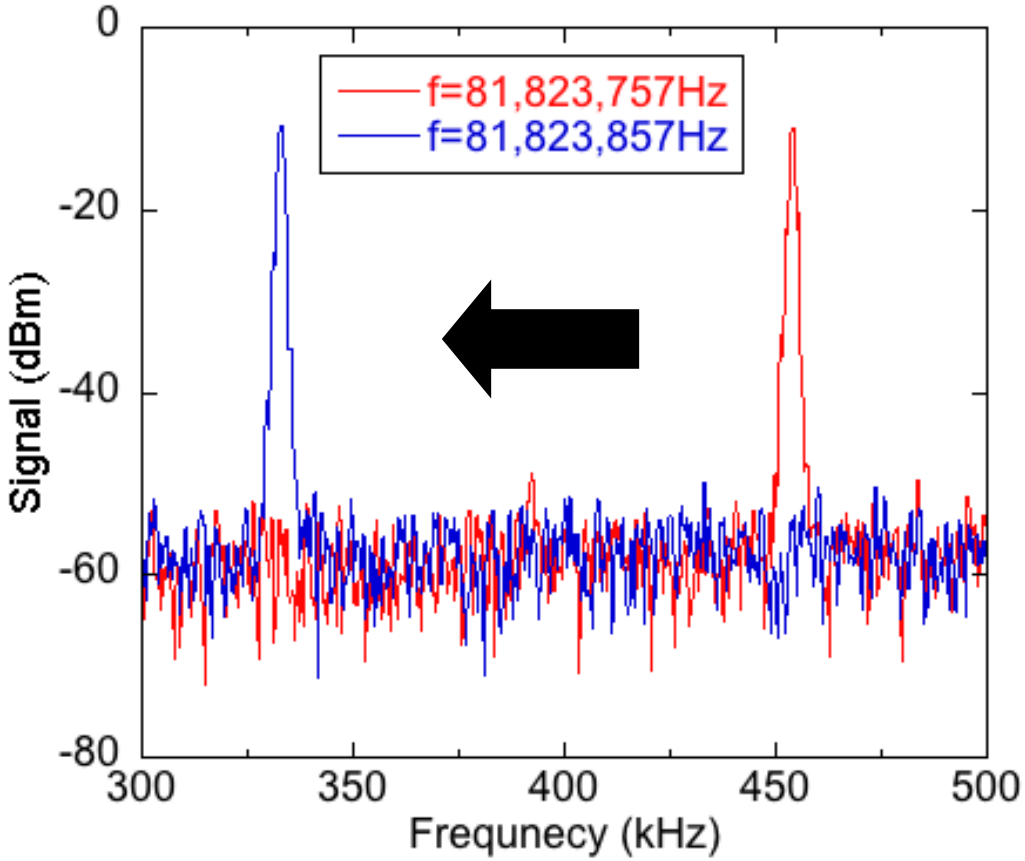
Freq. modulation of test source(100GHz±87.6kHz@0.5Hz)



RBW=3kHz, sweep time=50ms,full span=300kHz

Determination of absolute frequency

~Shift of ML frequency by 100Hz~



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

$$= \frac{454{,}027.976 - 333{,}027.731}{81{,}823{,}857 - 81{,}823{,}757}$$

$$= 1210.00245$$

$$f_x = mf + f_b$$

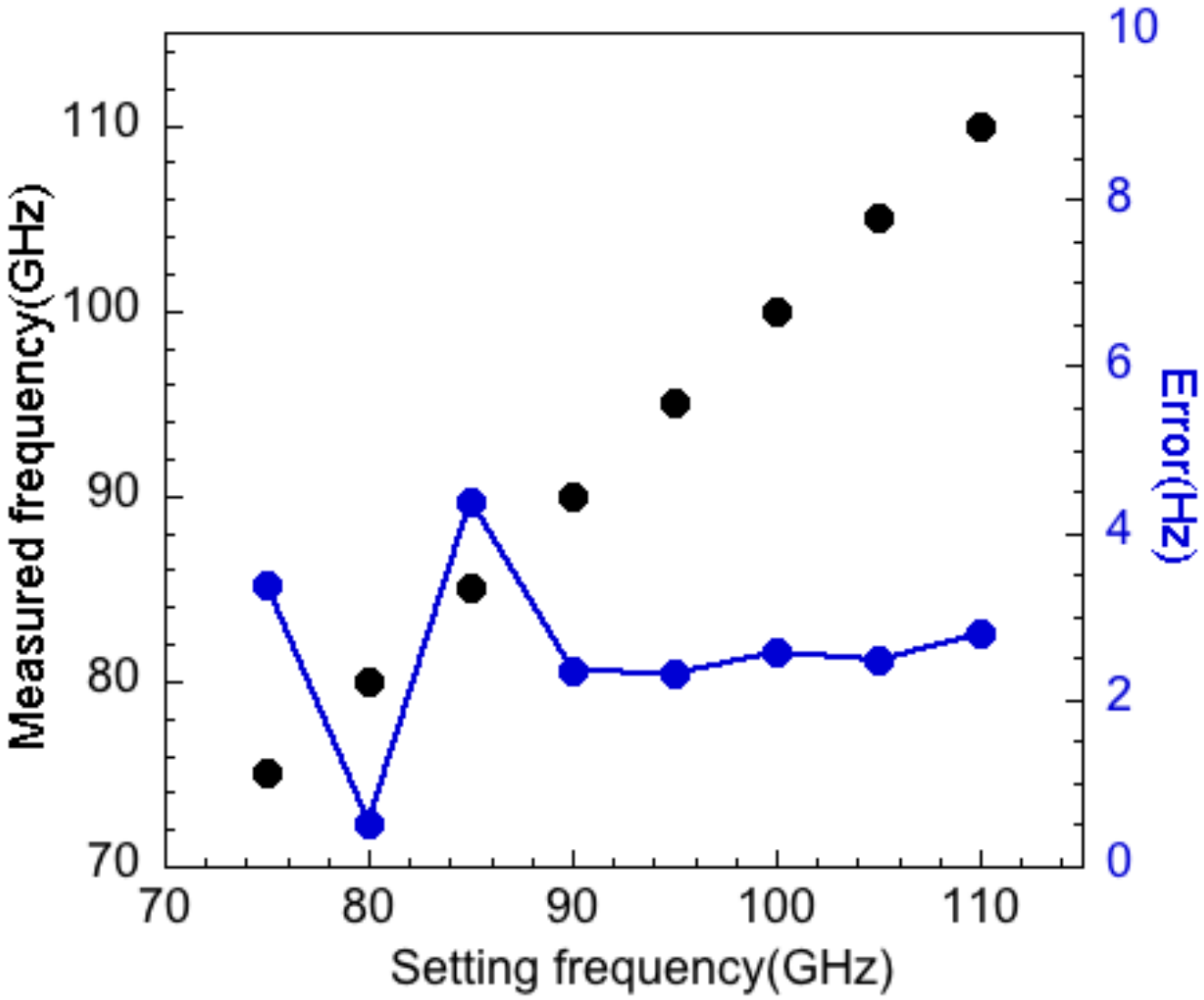
$$= 1210 * 81{,}823{,}757 + 454{,}027.976$$

$$= 99{,}007{,}119{,}997.976\ Hz$$

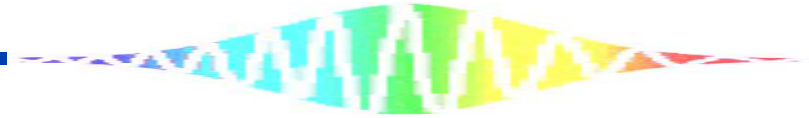
error=2.004Hz

Setting freq. of test source=99,007,200,000 Hz

Frequency tuning of test source



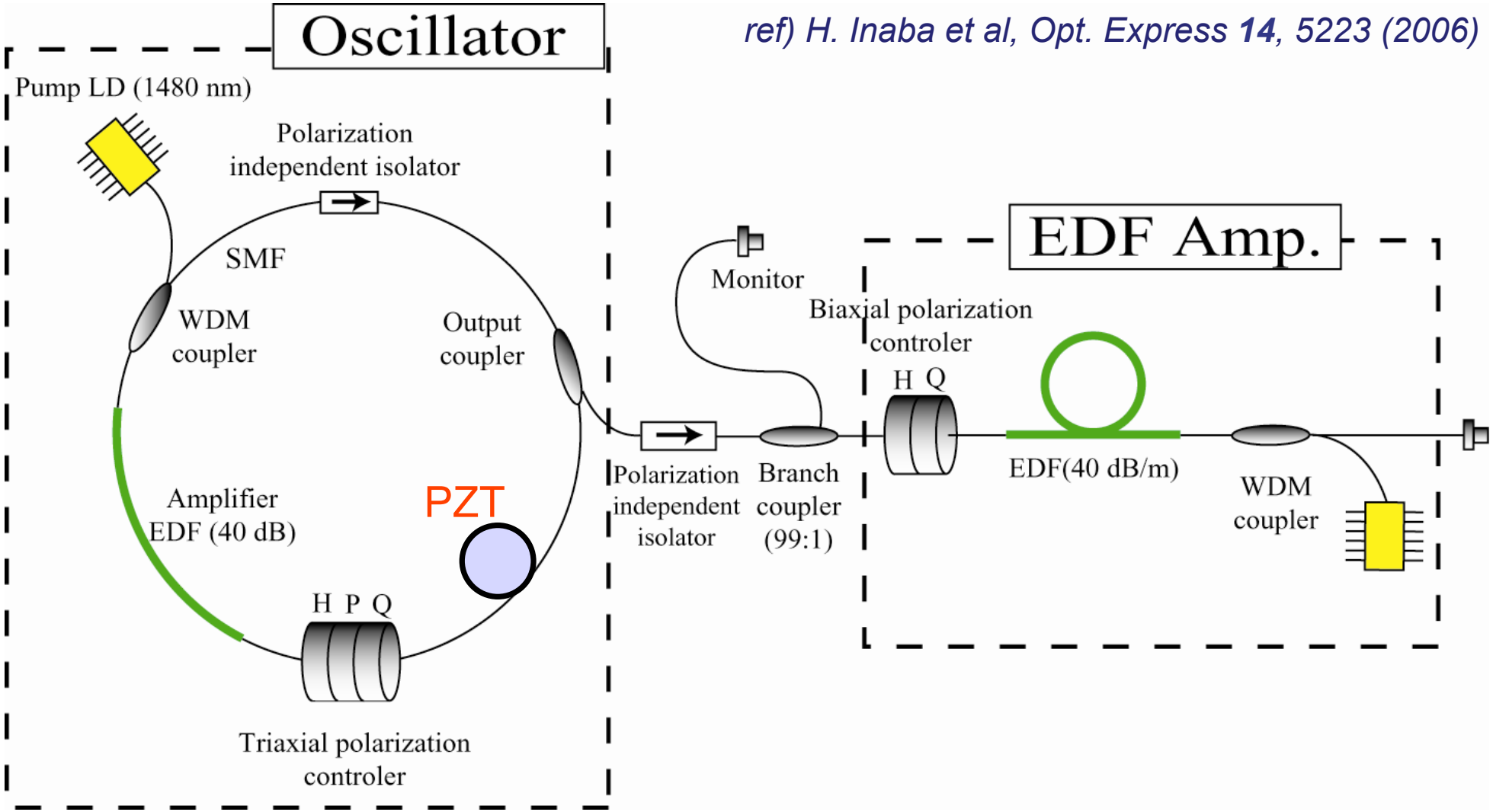
Precision=$2.8*10^{-11}$



3. Fiber-laser-based THz spectrum analyzer

~simple, compact, inexpensive, and robust system~

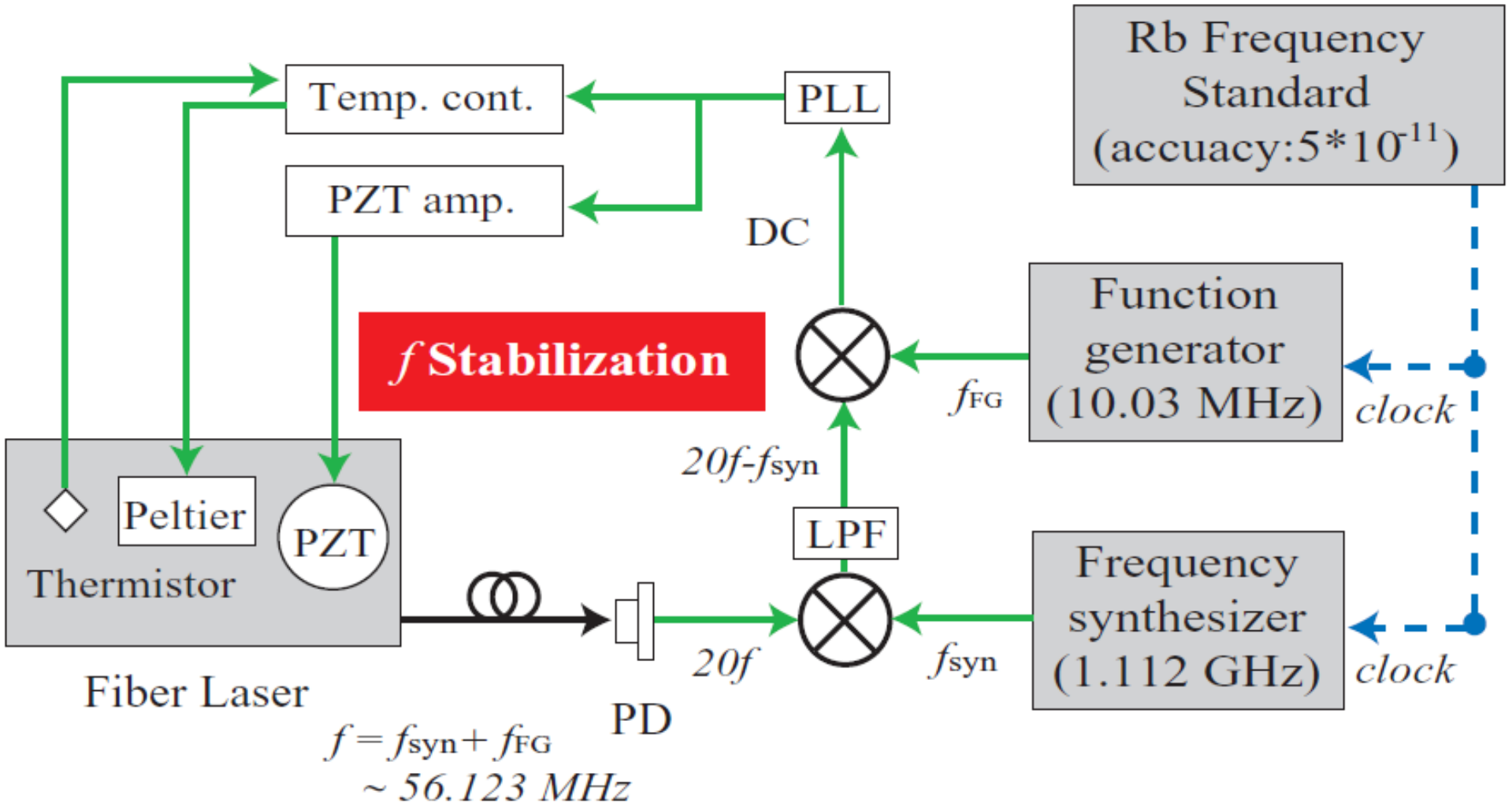
Er-doped fiber laser



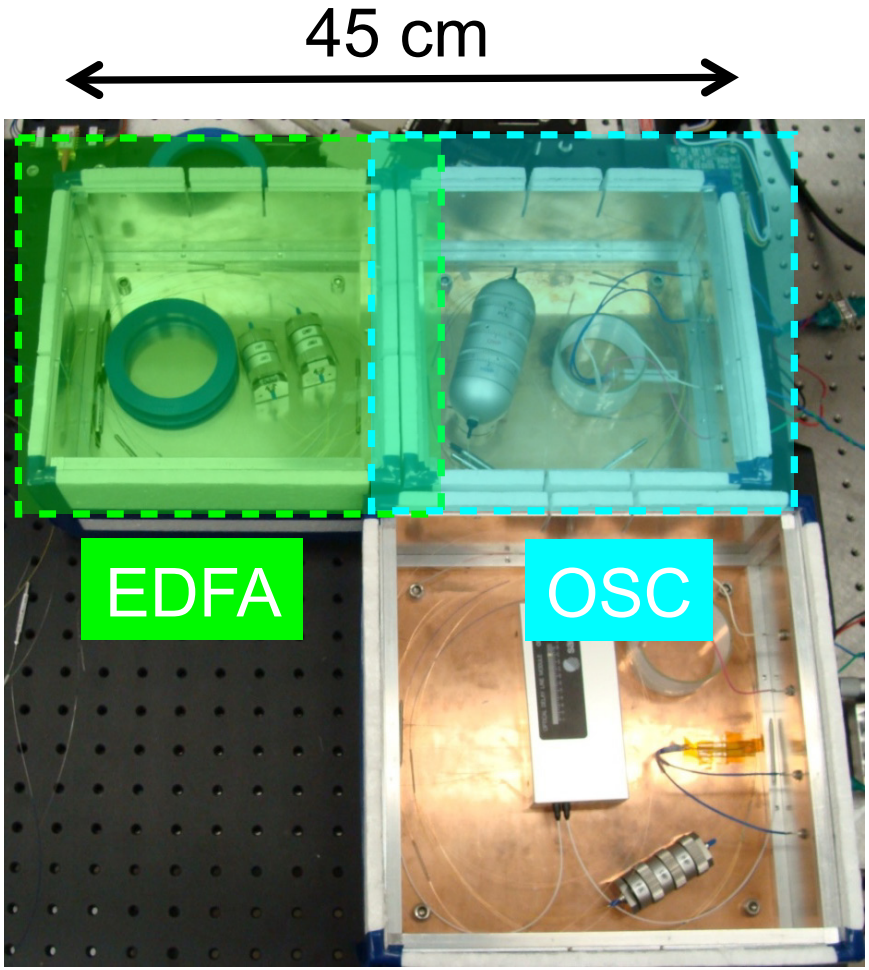
ref) H. Inaba et al, Opt. Express **14**, 5223 (2006)

Temp. control (Peltier)

Stabilization system of ML frequency

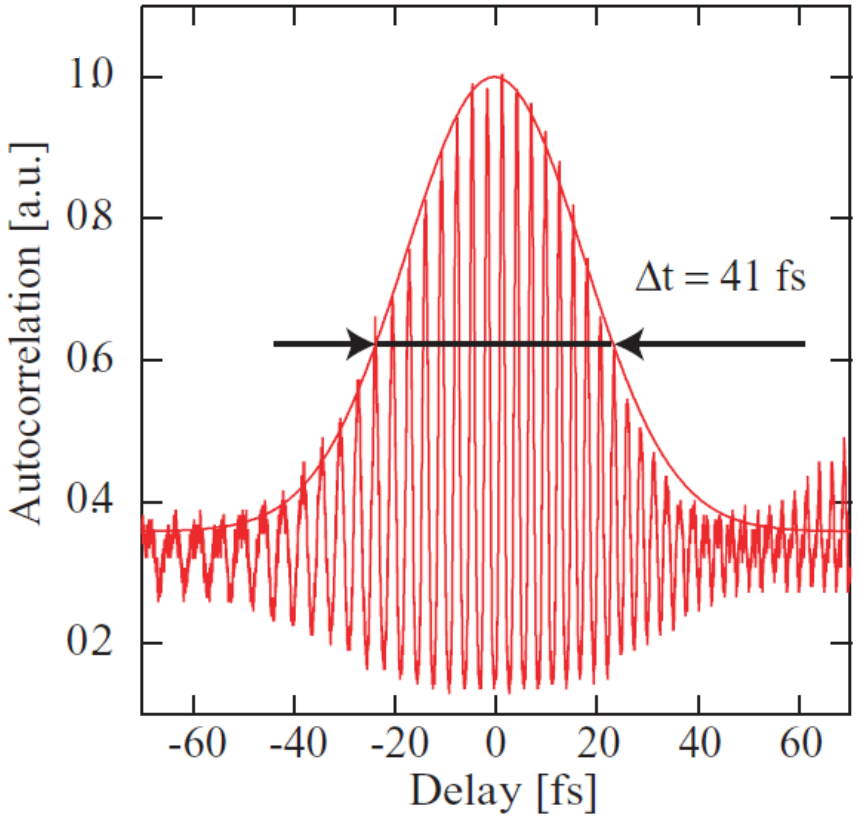


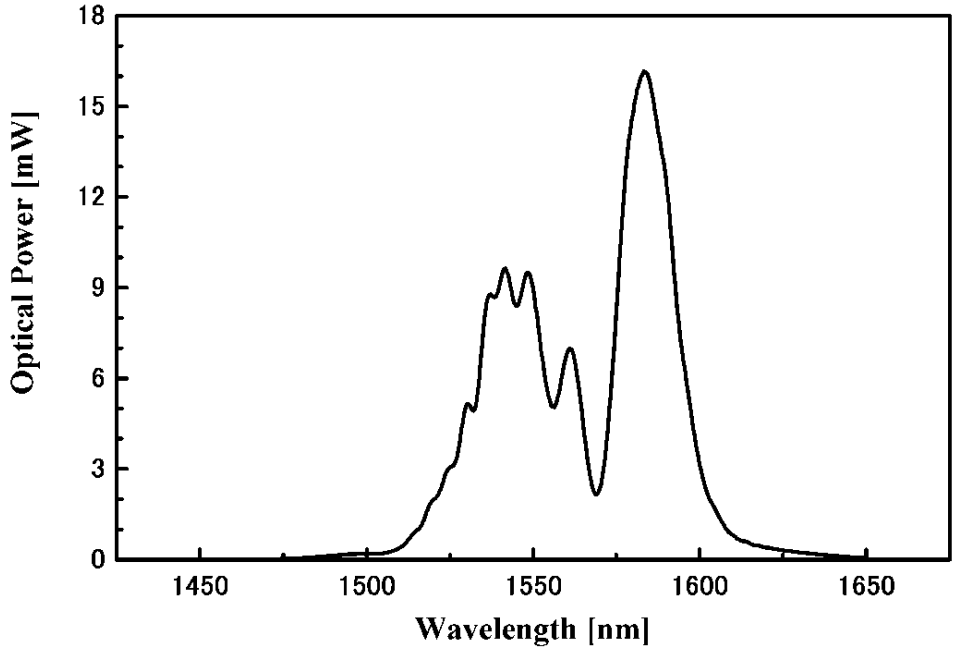
Photograph and cost of home-build fiber laser



COST	
OSC	¥ 700,000
EDFA	¥ 650,000
Control electronics	¥ 400,000

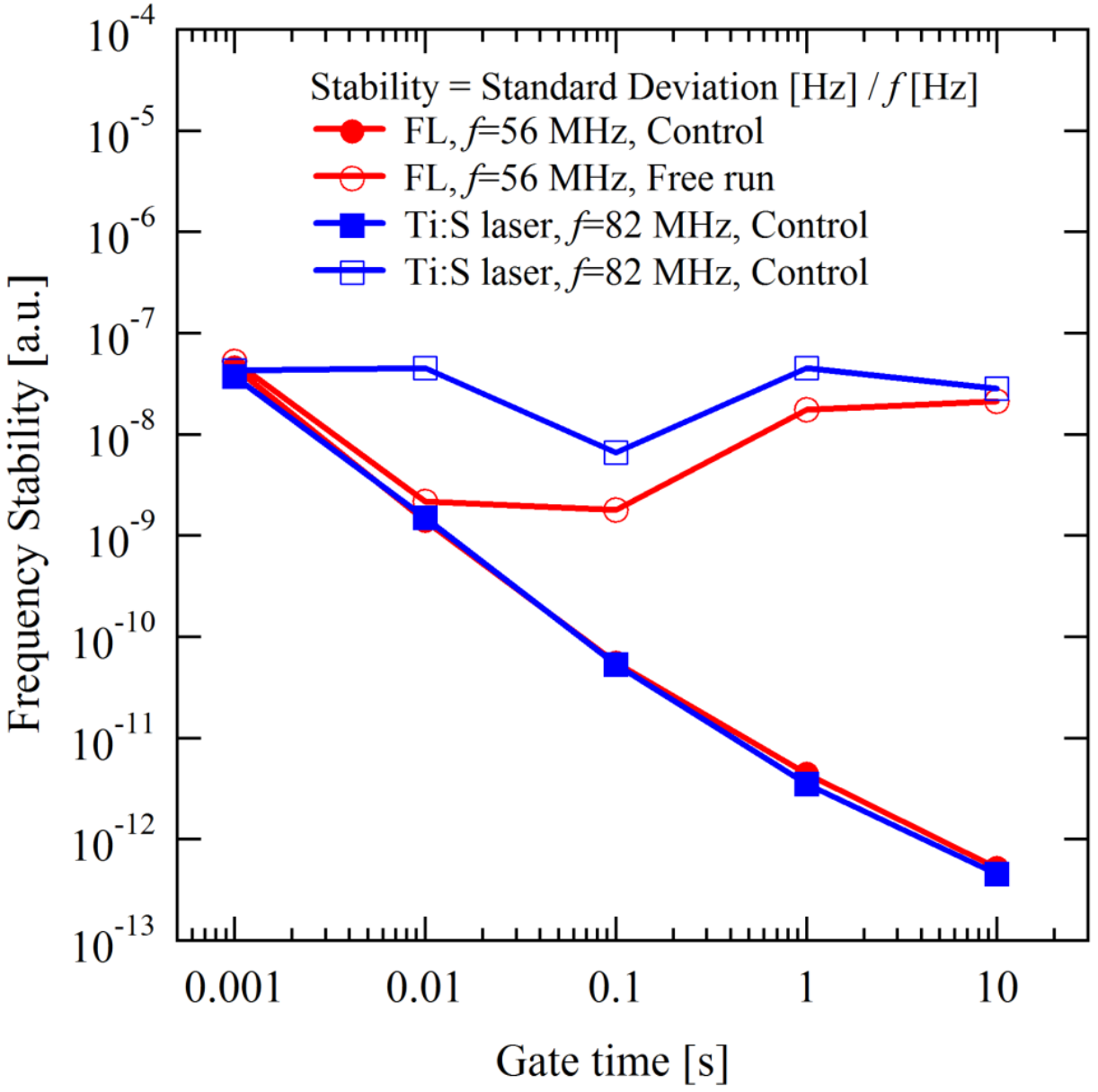
Autocorrelation signal and spectrum



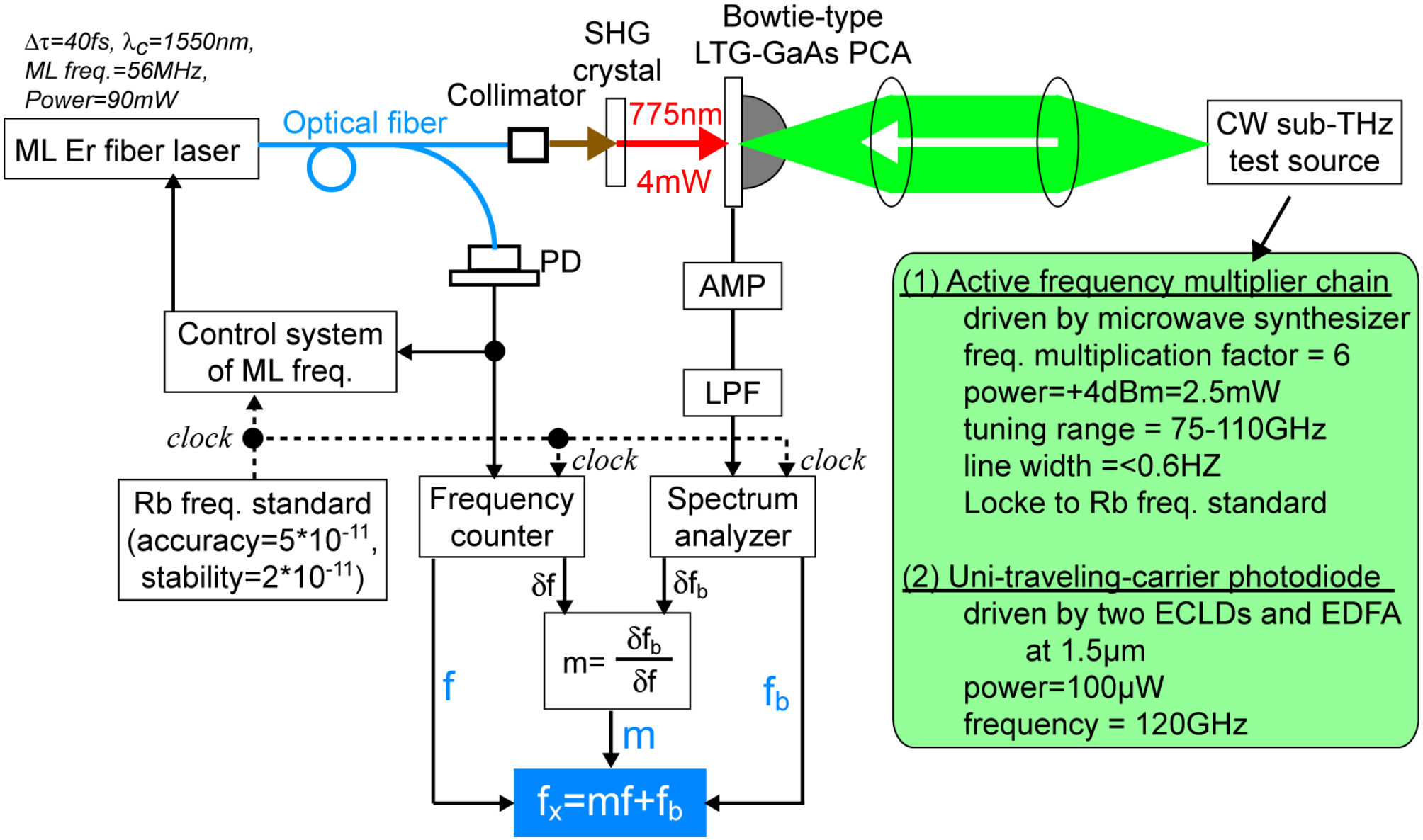


Average power = 90mW@1550nm or 10mW@775nm
Mode-locked frequency = 56MHz

Stability of ML frequency of fiber laser



Experimental setup



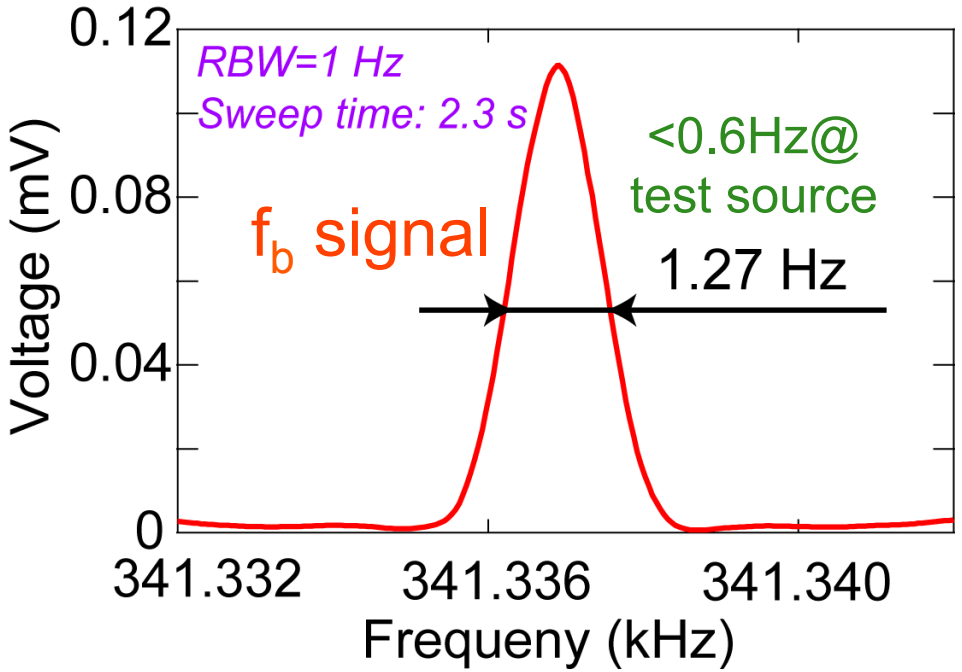
(1) Active frequency multiplier chain
- driven by microwave synthesizer
- freq. multiplication factor = 6
- power=+4dBm=2.5mW
- tuning range = 75-110GHz
- line width =<0.6HZ
- Locke to Rb freq. standard

(2) Uni-traveling-carrier photodiode
- driven by two ECLDs and EDFA at 1.5μm
- power=100μW
- frequency = 120GHz

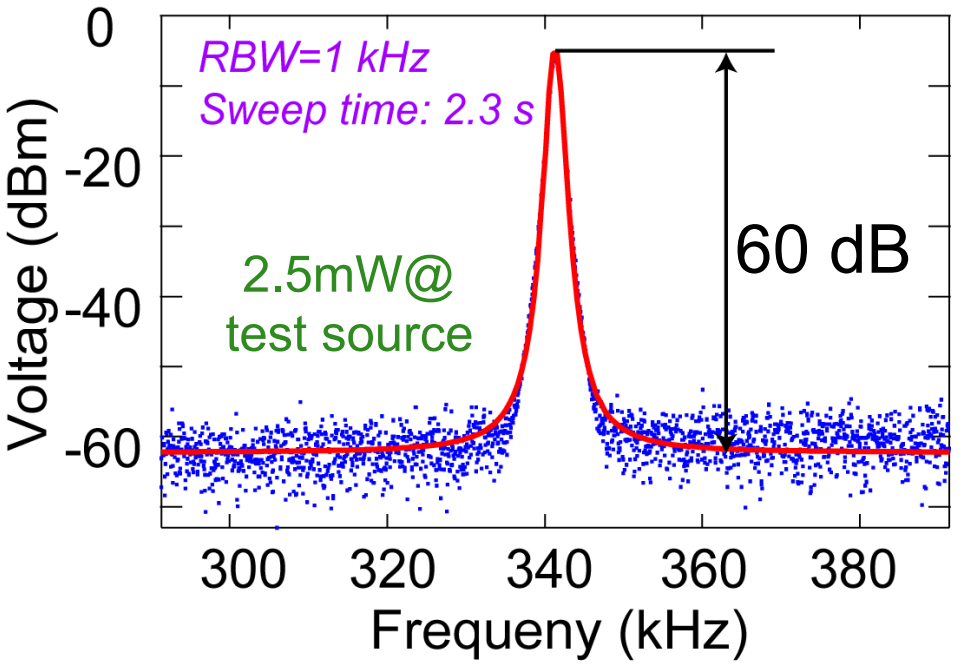
Observation of beat signal (1)

（80GHz active frequency multiplier）

Linewidth



Signal-to-noise ratio

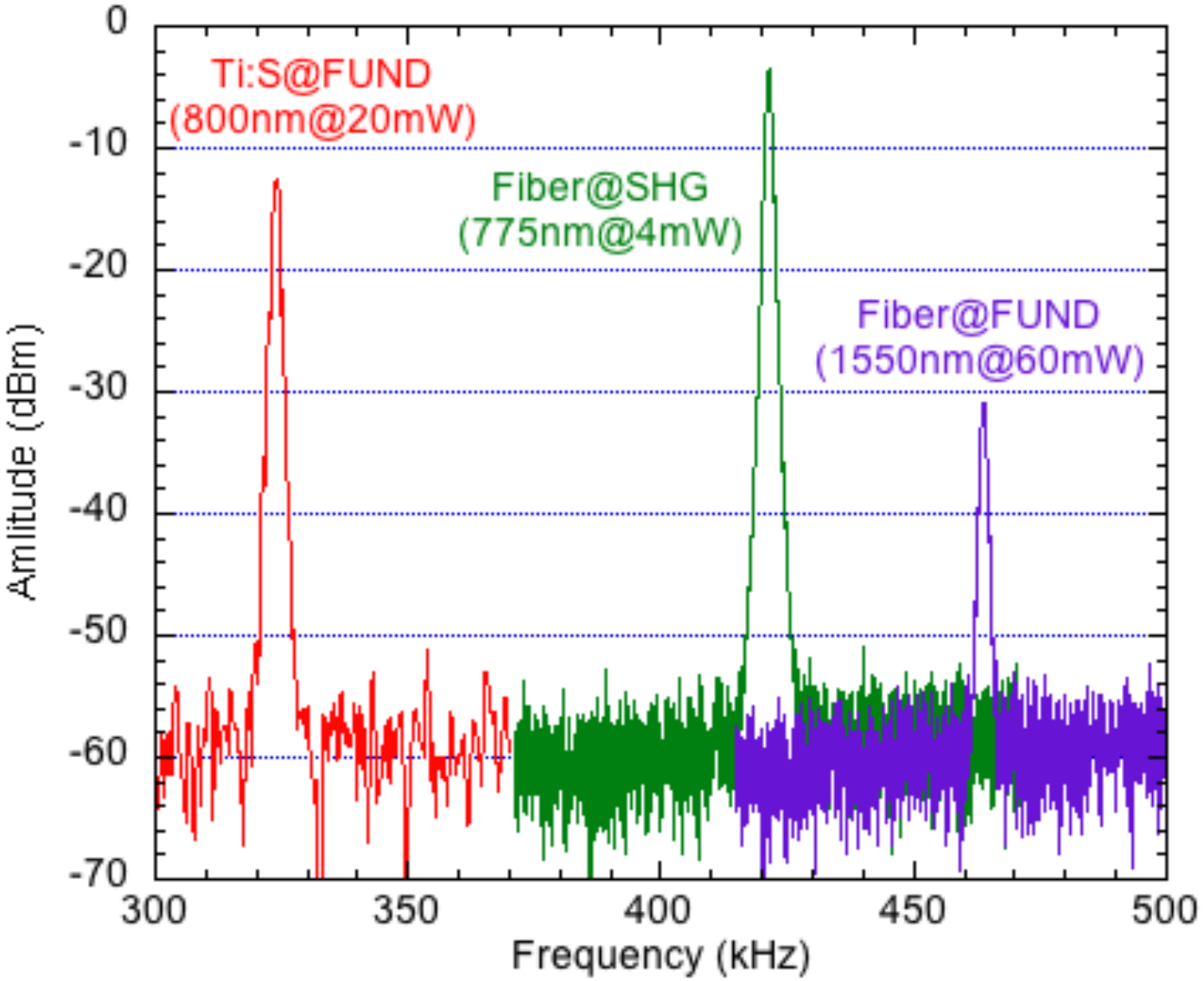


Linewidth < 1Hz

Detection limit = 2.5nW

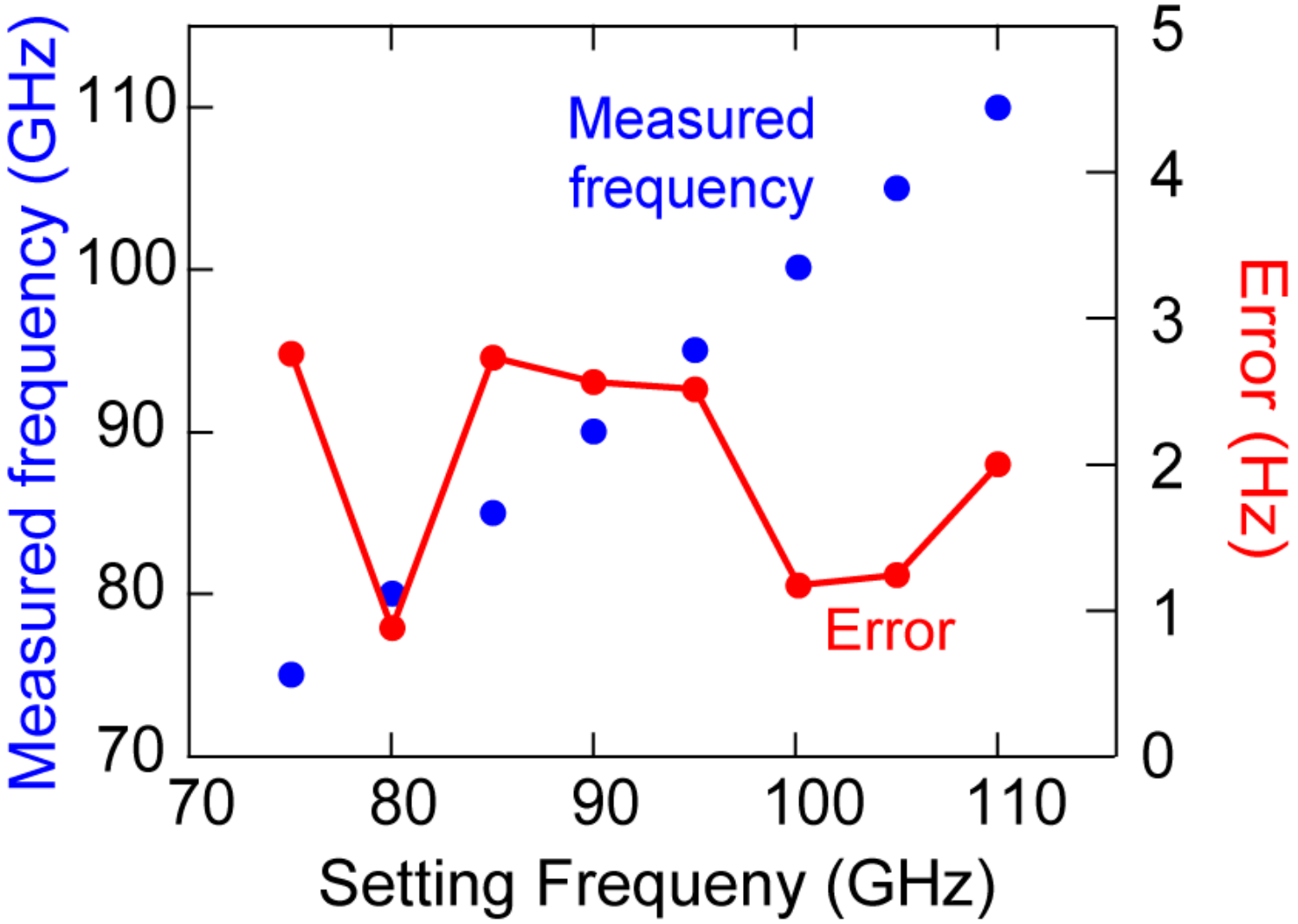
Comparison of f_b beat signal

Bowtie-type LTG-GaAs PCA



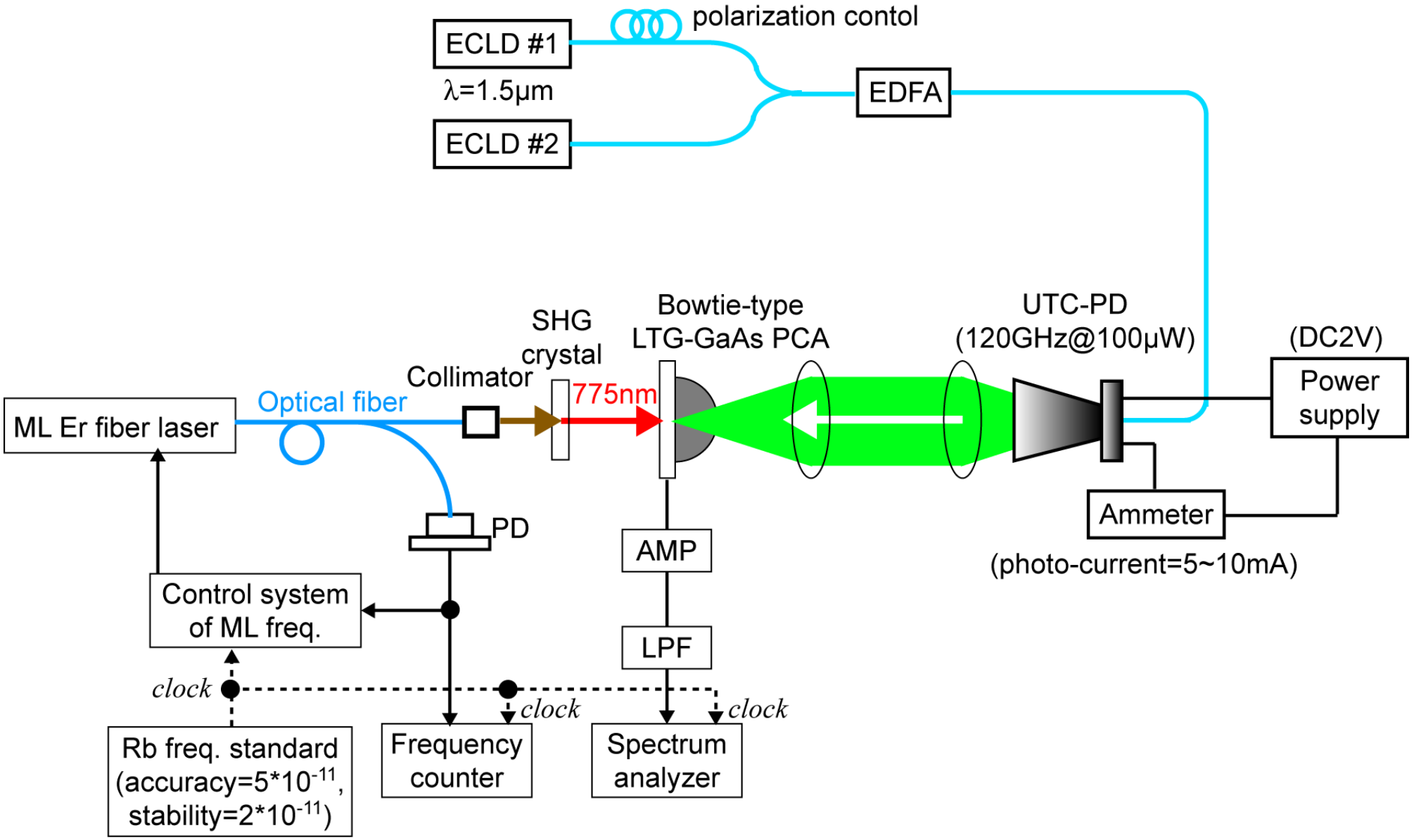
Frequency tuning of test source

（active frequency multiplier）



Mean precision=$2.2*10^{-11}$

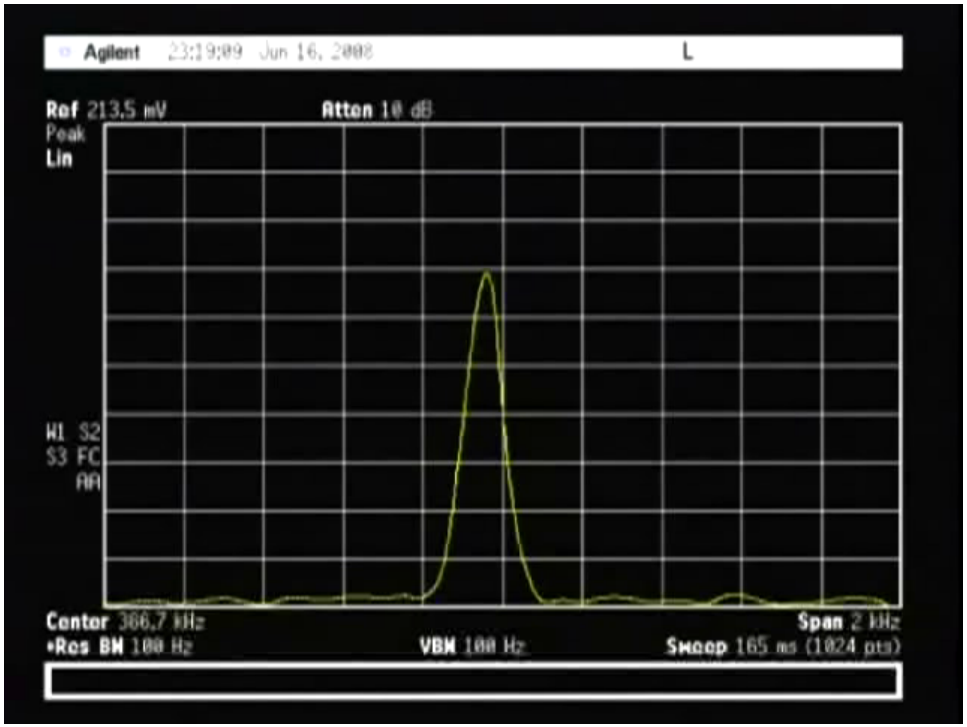
Experimental setup for UTC-PD



Real-time monitoring of beat signal

80GHz active freq. multiplier (2.5 mW)

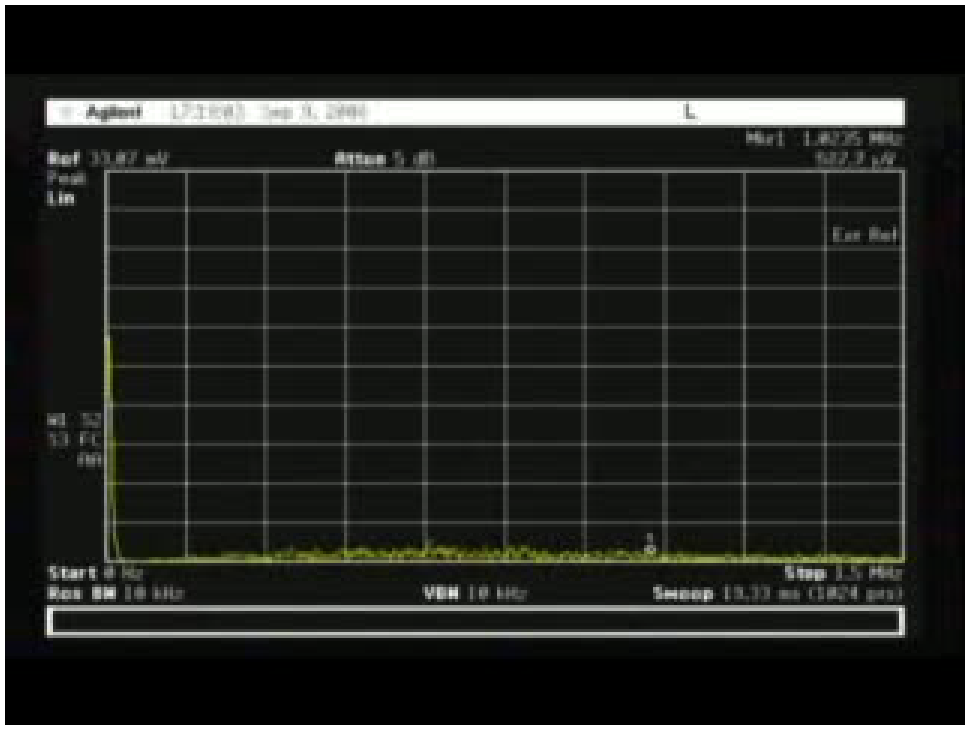
Freq. span = 2 kHz



Sweep time=165 ms, RBW=100 Hz

120GHz UTC-PD (0.1 mW)

Freq. span = 1.5 MHz



Sweep time=20 ms, RBW=10 kHz

Comparison with conventional method

	Conventional methods		Proposed method
	Heterodyning method	Interferometric method	
Principle	Electric heterodyning	Optical Interferometry	PC-THz comb
Range	< 2THz	>several THz	0.1THz∽10 THz
Frequency accuracy	10^{-11} (depending on local oscillator)	10^{-9} (depending on interferometry)	10^{-11} (depending on PC-THz comb)
Detector	Antenna	Bolometer (cooling)	PCA
Mixer	SIS, bolometer, etc (cooling)	Beamsplitter	
Apparatus	Complicated	Complicated	Simple