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AIST

Optical frequency combs and their applications

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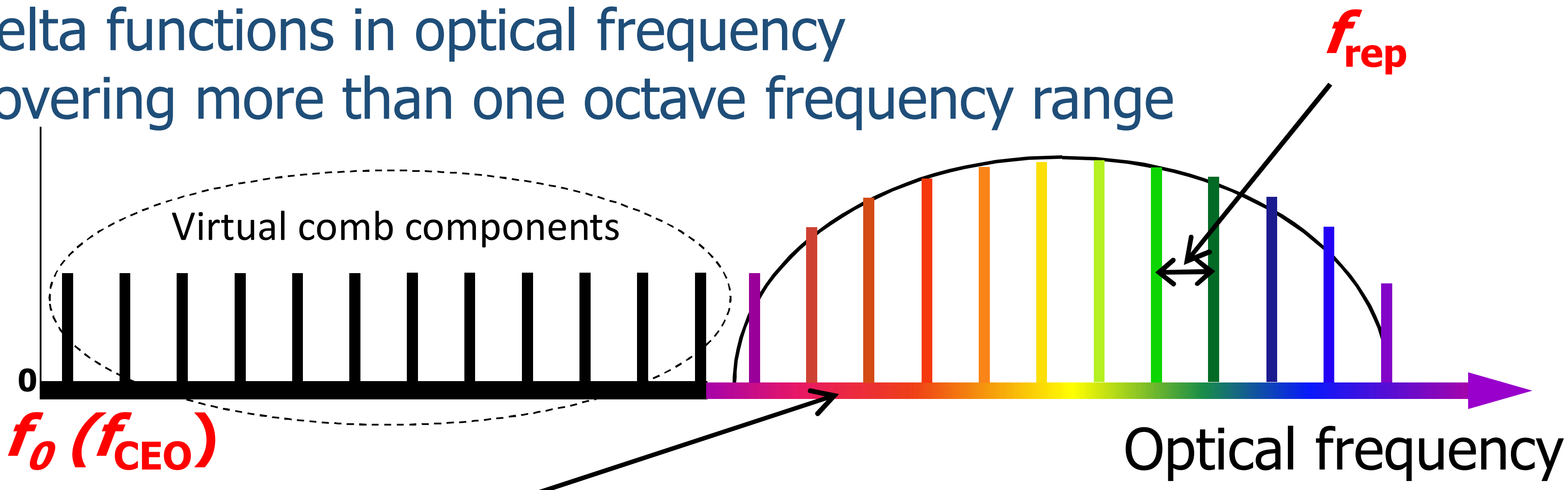
UEC TOKYO 国立大学法人 電気通信大学

ERATO 美濃島知的光シンセサイザプロジェクト MINOSHIMA Intelligent Optical Synthesizer Project

What is an optical frequency comb?

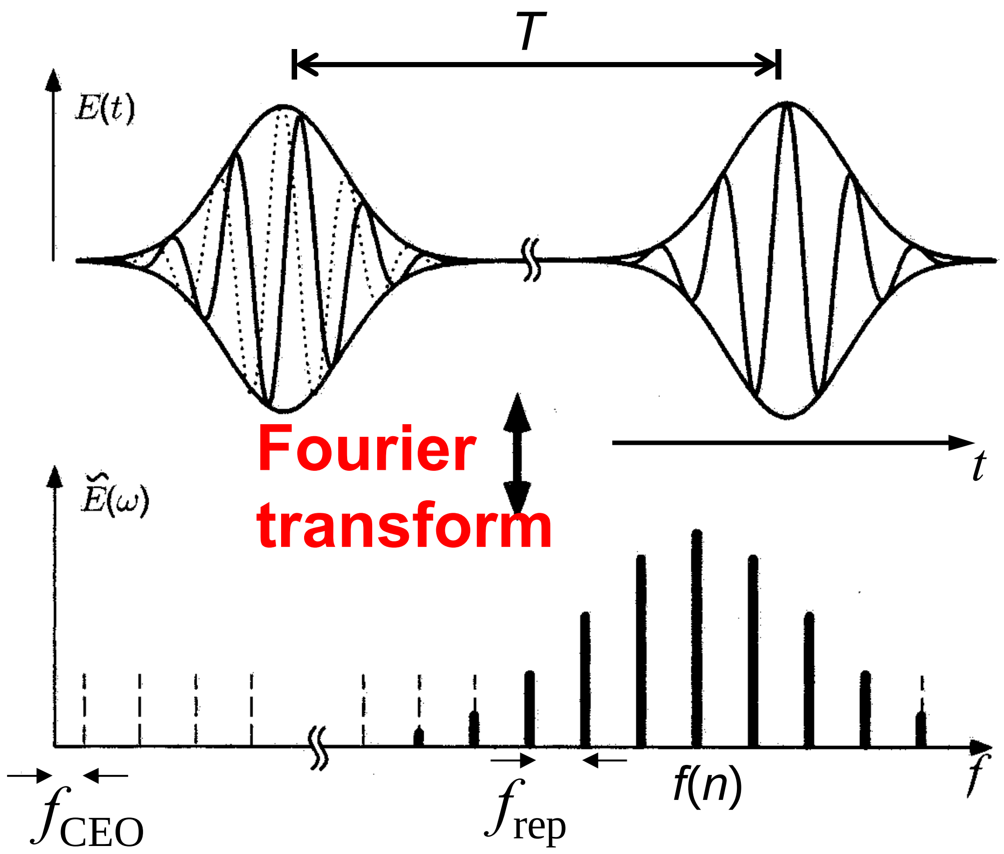
Optical frequency components with equal frequency spacing
Delta functions in optical frequency
Covering more than one octave frequency range



Precise optical frequency ruler for measurements

Comb, コム（コーム）、櫛（くし）

Optical frequency comb based on femtosecond mode-locked lasers



The Fourier transform relation between time and frequency axes:

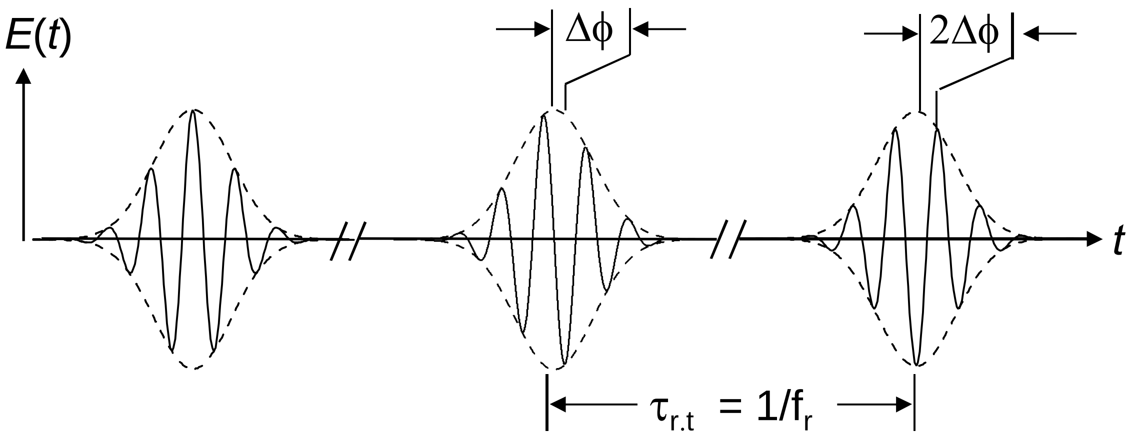
$f_{rep} = 1/T$

Shorter pulse width, larger frequency span

Ref.: Th. Udem *et al.*, Phy. Rev. Lett., 82, 3568 (1999).

Carrier envelope offset frequency

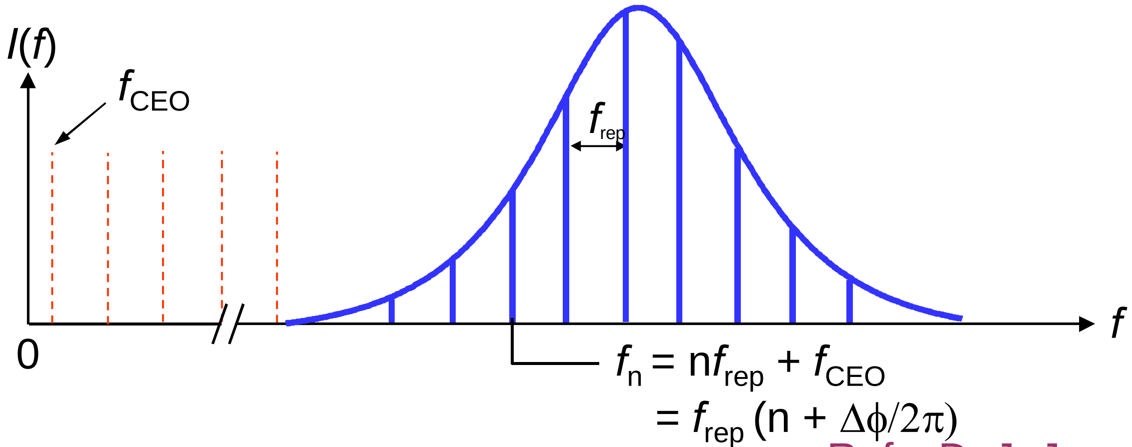
Time domain



Carrier-envelope phase slip from pulse to pulse because:

$$v_g \neq v_p$$

Frequency domain

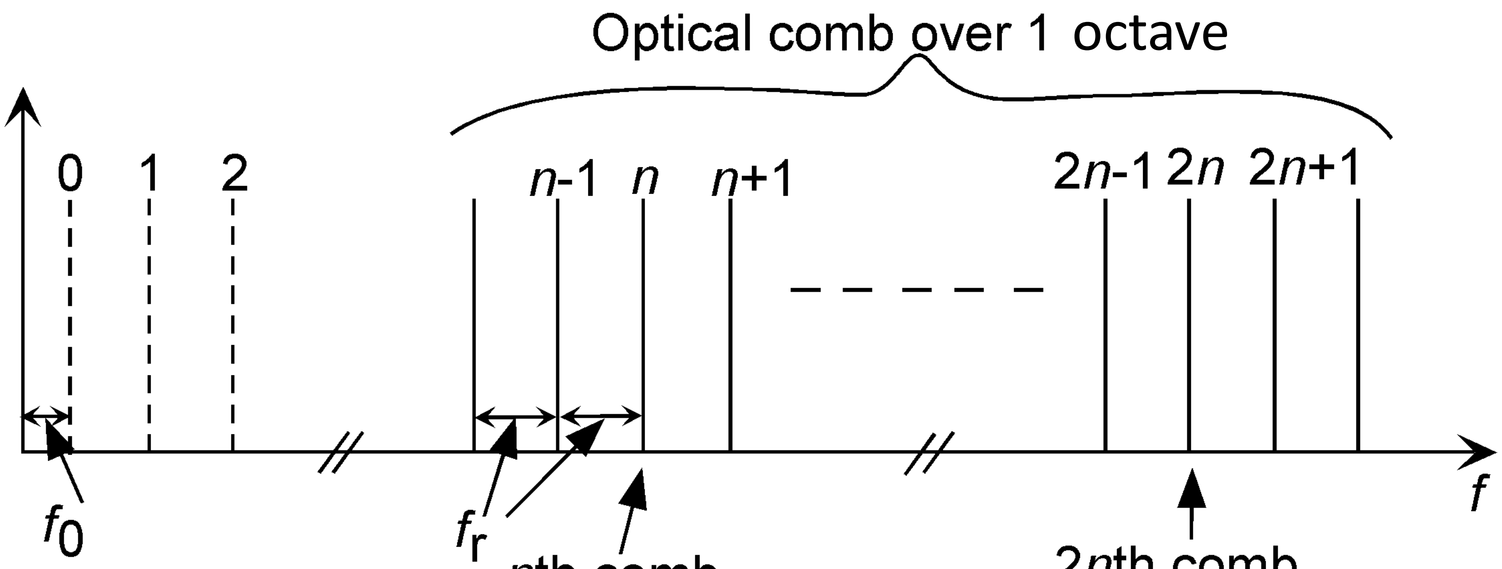


Modes are offset from harmonics of f_r by:

$$f_{CEO} = f_{rep}\,\Delta\phi/2\pi$$

Ref.: D. J. Jones *et al.*, Science, 288, 635 (2000).

f-$2f$ interferometer for observing f_0 (f_{CEO})



*n*th comb

$f(n) = n \times f_r + f_0$

2*n*th comb

$f(2n) = 2n \times f_r + f_0$

SHG

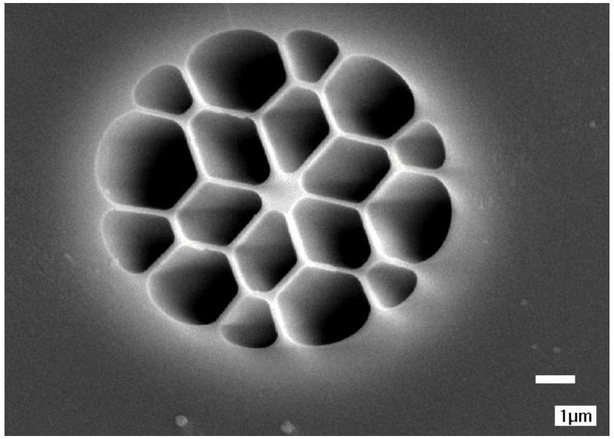
$2f(n) = 2n \times f_r + 2f_0$

Beat frequency $2f(n) - f(2n) = 2n \times f_r + 2f_0 - 2n \times f_r - f_0$

$= f_0$

Ref.: D. J. Jones *et al.*, Science, 288, 635 (2000).

Photonic crystal fiber (PCF)



Photonic crystal fiber (PCF)

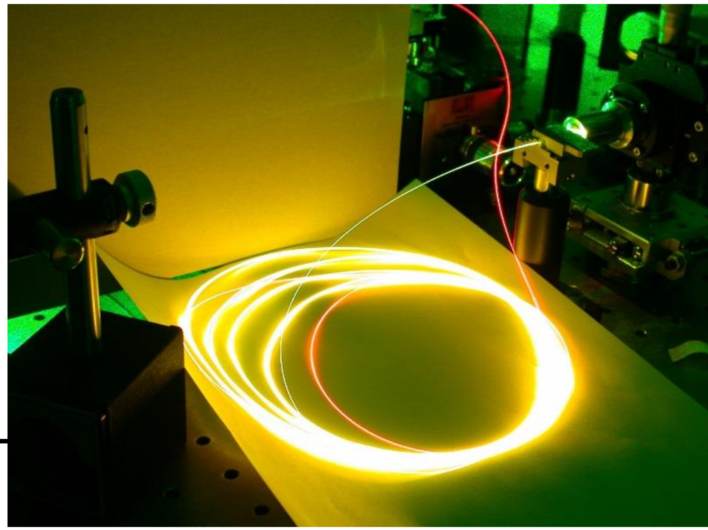
Ref.: J. C. Knight, Nature, 424, 847 (2003).

ÅZero dispersion at 800 nm, the center wavelength of a Ti:sapphire laser

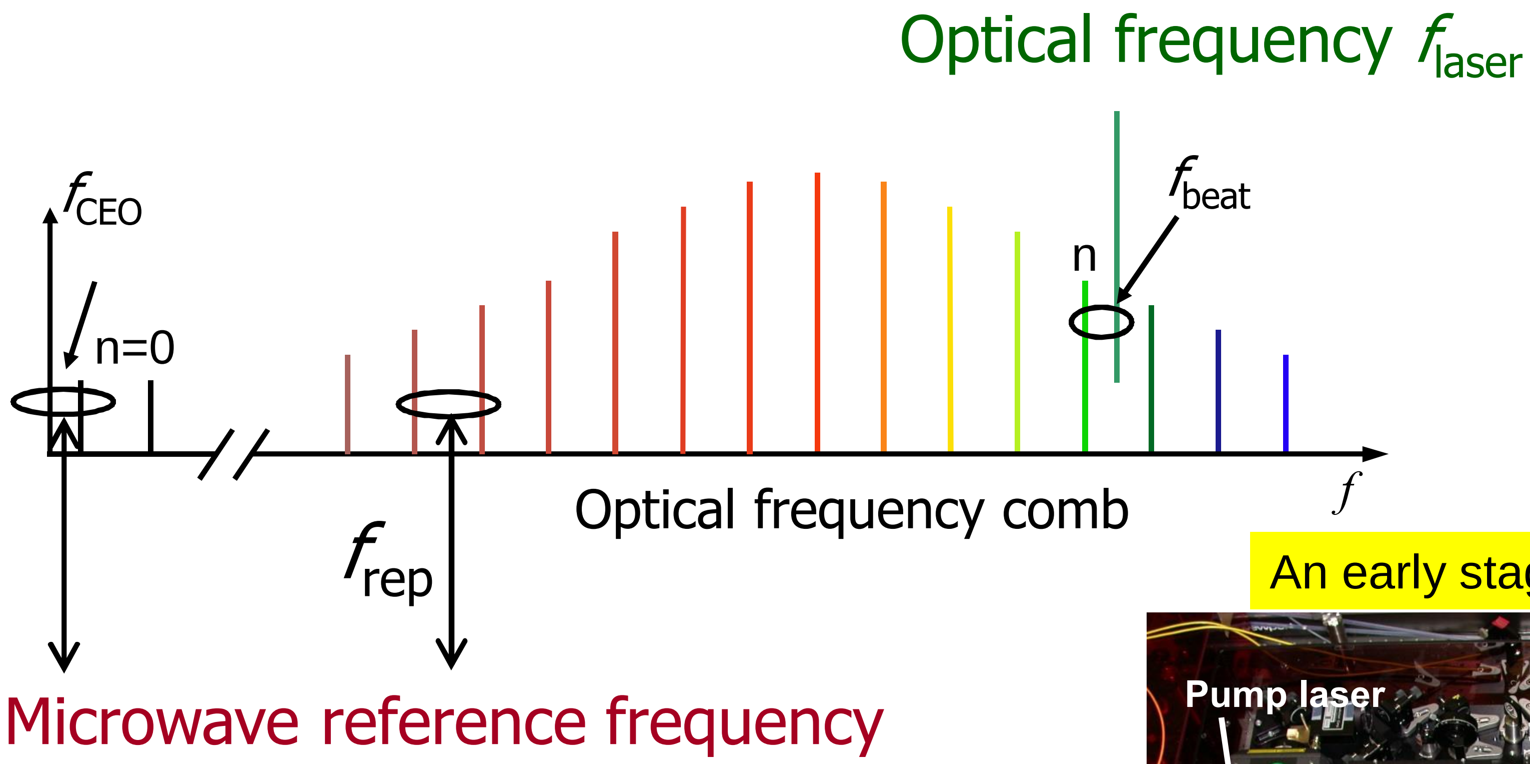
ÅPulse remains high peak

ÅSpectrum broadened by self phase modulation or four wave mixing process

More than one octave spectrum

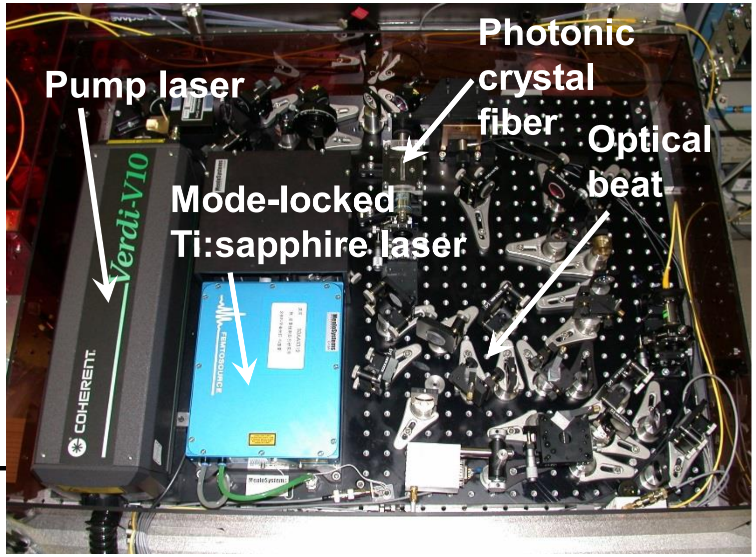


A precise optical frequency ruler



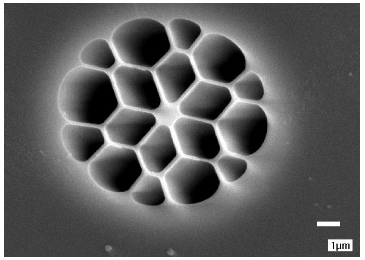
$$f_{laser} = f_{CEO} + n \cdot f_{rep} + f_{beat}$$

An early stage Ti:s comb



From Ti:sapphire combs to fiber combs

1)Coupling the laser light into the PCF is the main issue that limits the reliability of the comb.

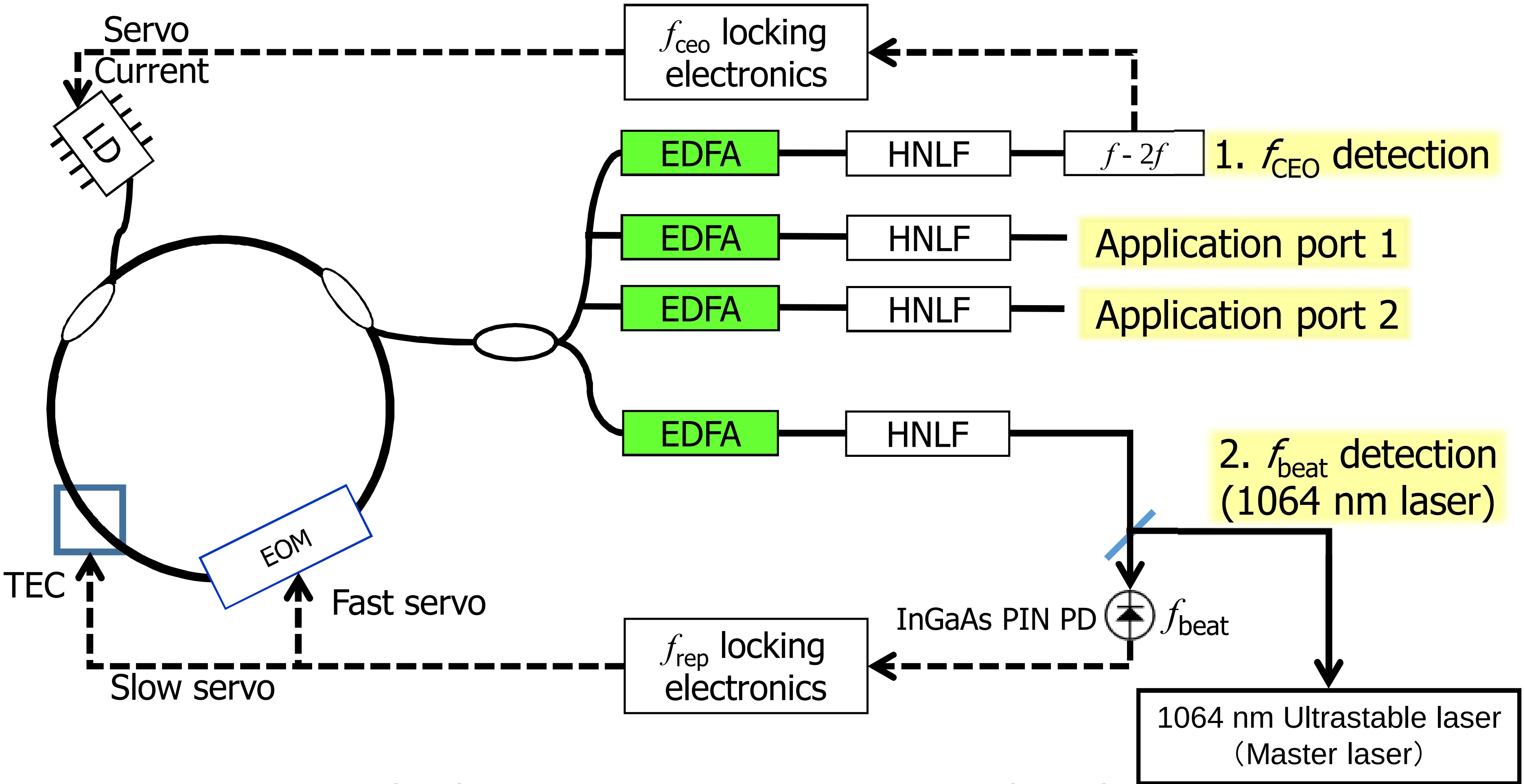


2) Pump laser is the main issue that limits the cost efficiency and also the compactness.

↓

Mode-locked Er fiber laser at 1.5 μm

Multi-branch amplifiers for beat detections



K. Iwakuni *et al.*, Opt. Express 20, 13769 (2012).

Applications of optical frequency combs

UVコム高調波発生

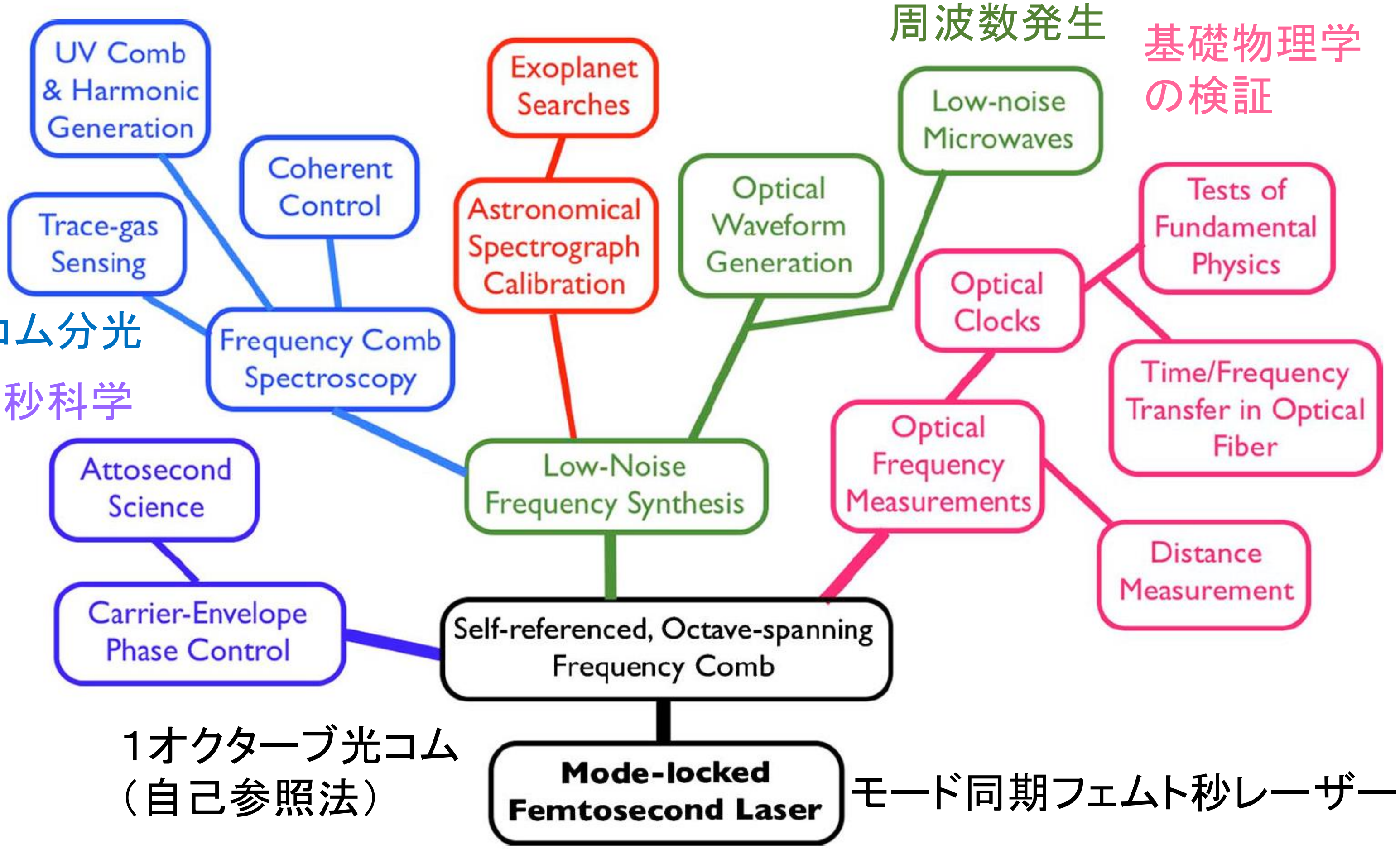
系外惑星探査

ローノイズ
周波数発生

基礎物理学
の検証

光コム分光

アト秒科学

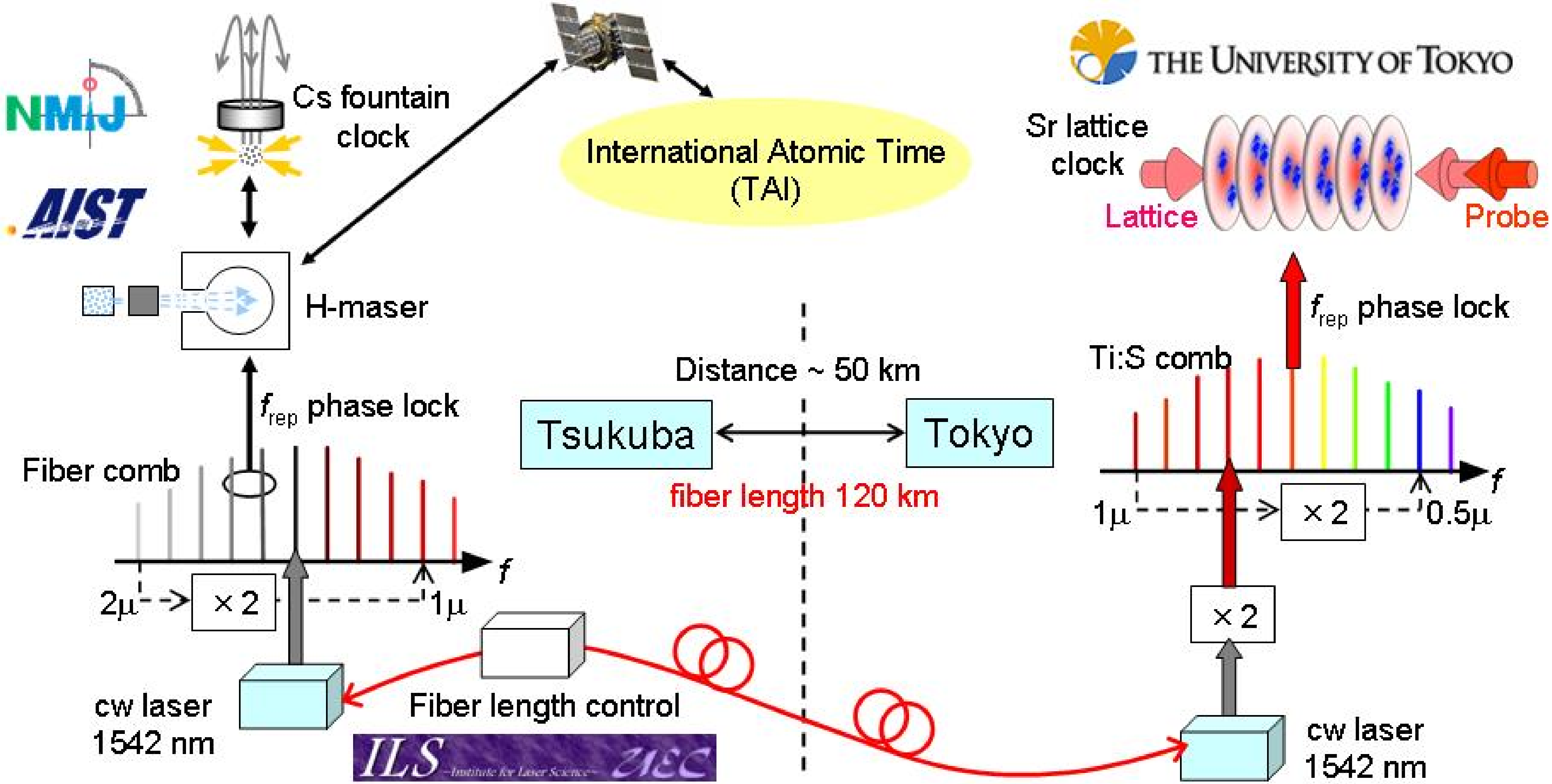


1オクターブ光コム
（自己参照法）

モード同期フェムト秒レーザー

S.A. Diddams et al.: J. Opt. Soc. Am. B 27, B 51(2010).
大苗、洪：応用物理 84, 30 (2015).

Application in precision measurement

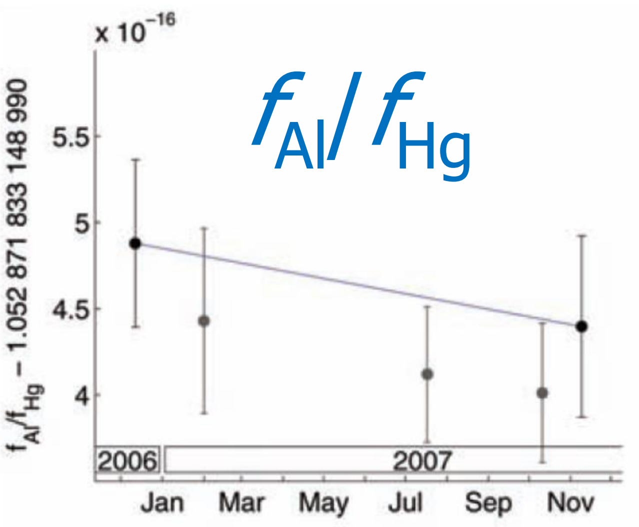


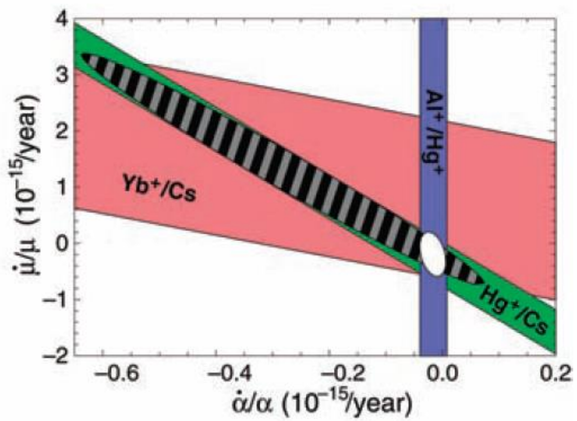
F.-L. Hong *et al.*, Opt. Lett. 34, 692 (2009).

Test of the time variation of fine structure constant

$$\frac{\partial \ln \alpha}{\partial t} < 1 \cdot 10^{-17}\, yr^{-1}$$ Oklo: Shlyakhter ($2x10^{9}$ yr)

$$\frac{\partial \ln \alpha}{\partial t} = (6.4 \pm 1.4) \cdot 10^{-16}\, yr^{-1}$$ Quasers: J. K. Webb et al. (10^{10} yr)

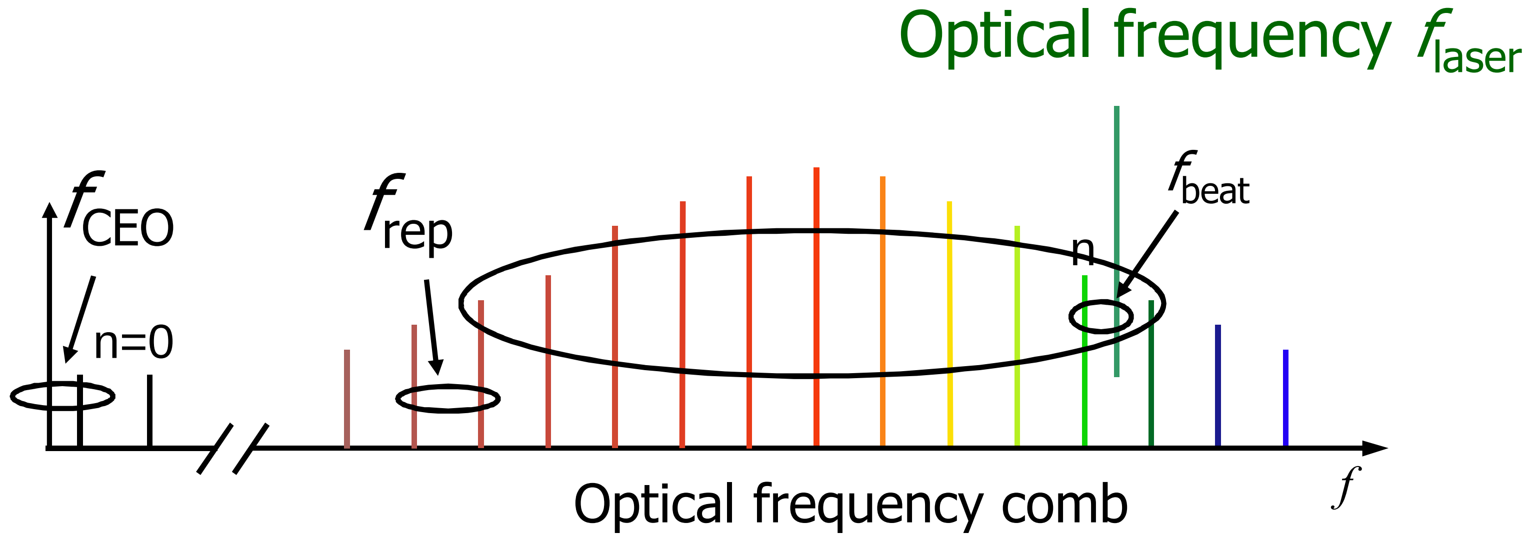




$$\dot{\alpha}/\alpha = (-1.6 \pm 2.3) \times 10^{-17}\,/\text{year}$$

T. Rosenband *et al.*, Science **319** (2008) 1808.

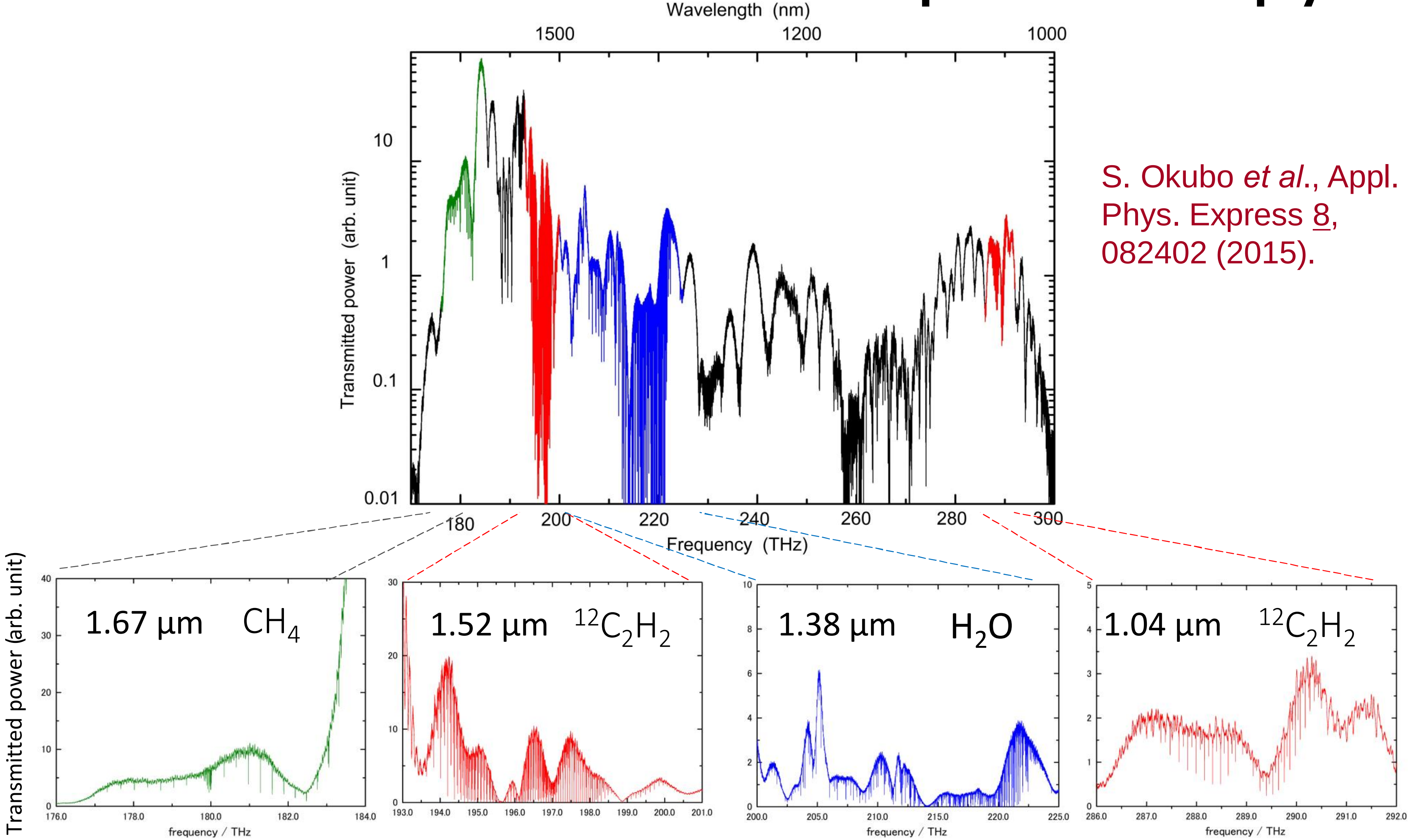
New applications of frequency combs



1)Dual comb spectroscopy

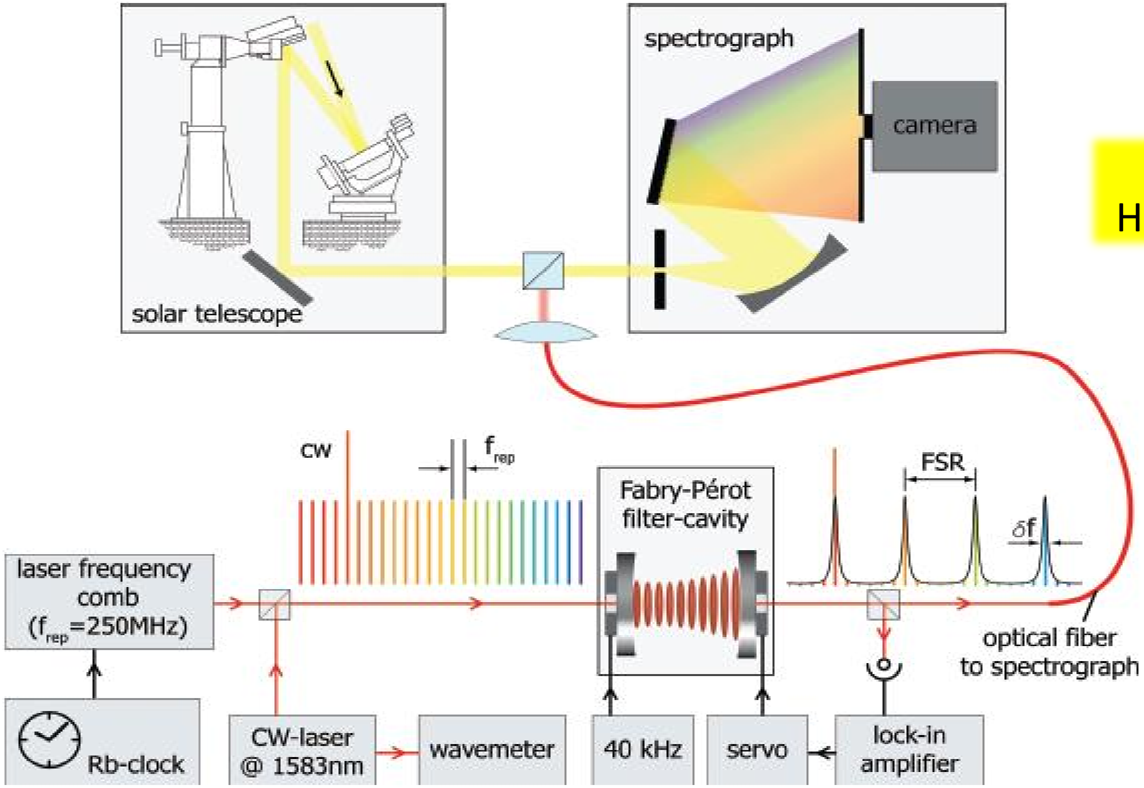
2)Astro comb

Dual comb broadband spectroscopy



S. Okubo *et al.*, Appl. Phys. Express 8, 082402 (2015).

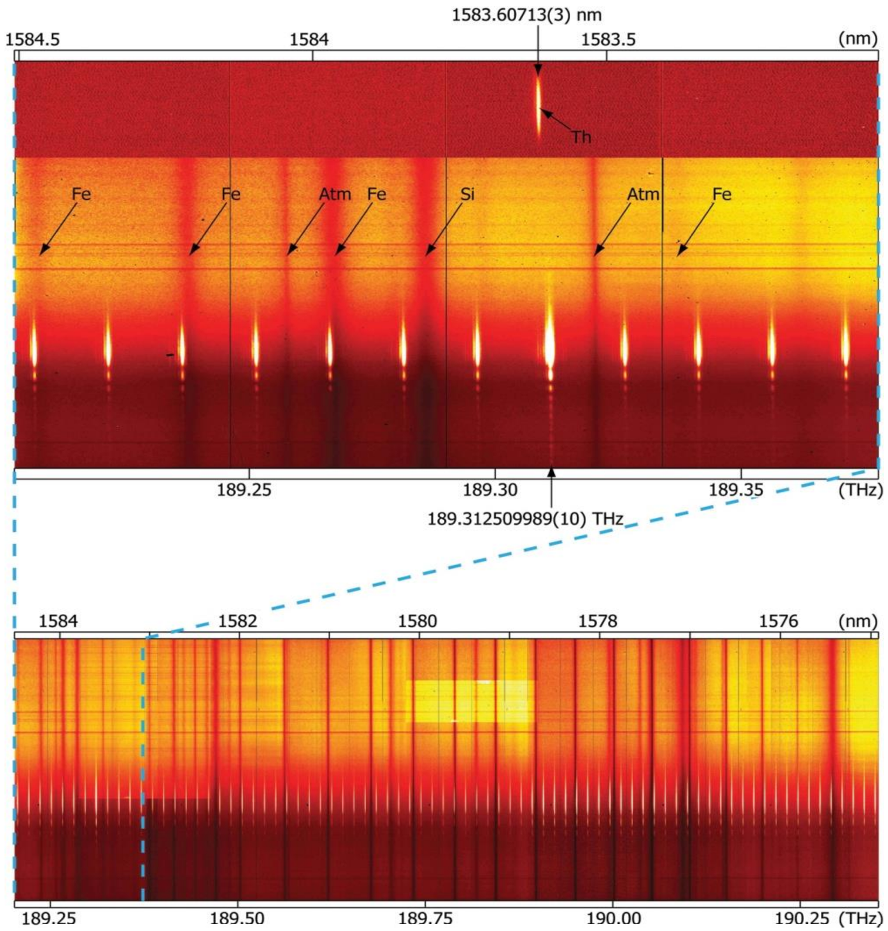
Optical frequency comb for telescope



Calibration of
High Dispersion Spectrograph

Doppler shift at the <1 m/s level can be detected!

T. Steinmetz, et al., Science **321**, 1335 (2008).



T. Steinmetz, et al., Science **321**, 1335, 2008

Optical frequency comb
= Frequency (wavelength) ruler

Plan for the ERATO astro comb

The ERATO astro comb:

・Covering wavelength range from 380 ï 540 nm with a frequency spacing of 20 GHz

・To be installed at the Okayama Astrophysical Observatory

Summary

- Introduction of frequency combs
- Fiber based frequency combs
- Applications of frequency combs
- An astro comb for Okayama Astrophysical Observatory

Thank you for your attention!