Fiber-based Optical frequency comb

National Time Service Center（NTSC）

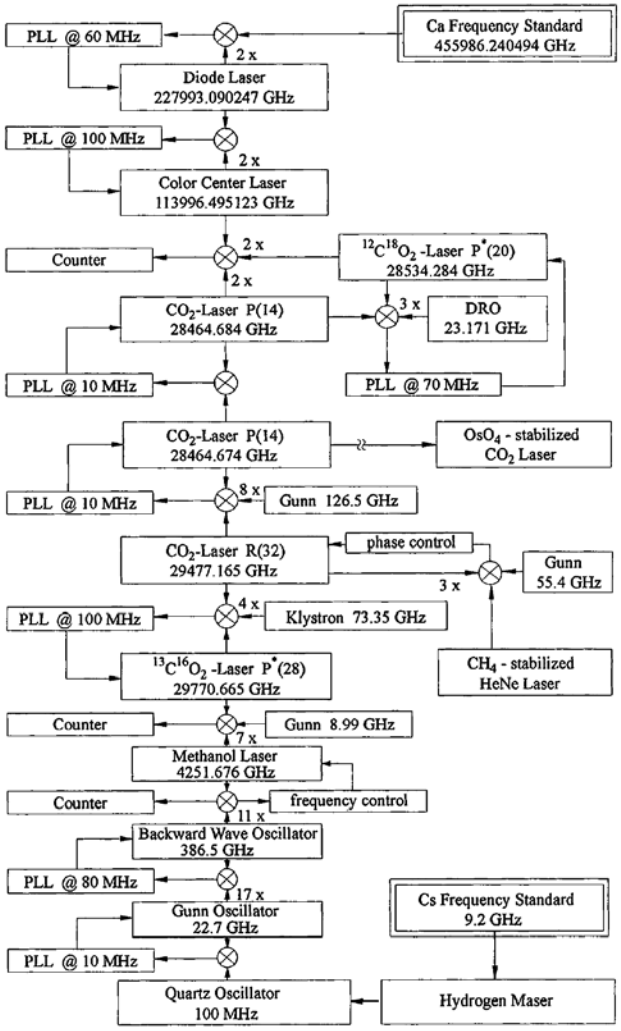
Haifeng JIANG

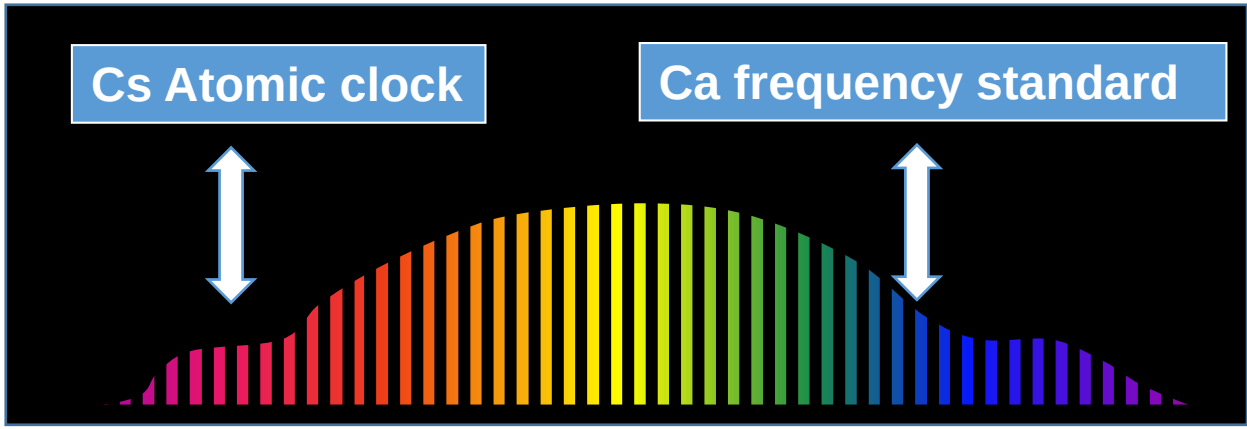
7th June 2019 · Shanghai

Outline

- Background Introduction
- Er:fiber based mode-locked laser
- Frequency control techniques
- Application of the Er:fiber based comb @ NTSC

Invention of the optical frequency comb paves the way of precise measurement (phase and frequency) in optical domain.





2005 Nobel Prize

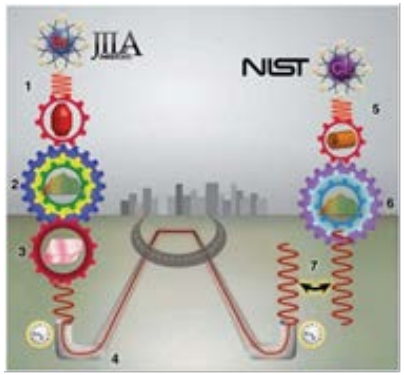
John L Hall
JILA—NIST&CU

Theodor W. Hänsch
MPQ

High precision radar

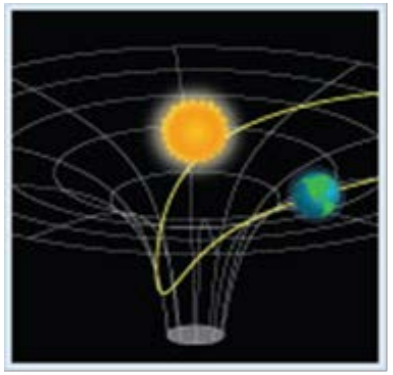
In 2010, Hansch pointed out that optical frequency combs had been used in more than 100 applications

Optical frequency standards

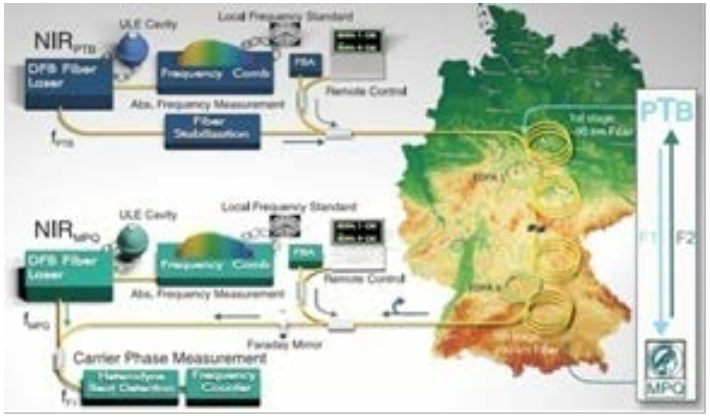


Frequency comparison

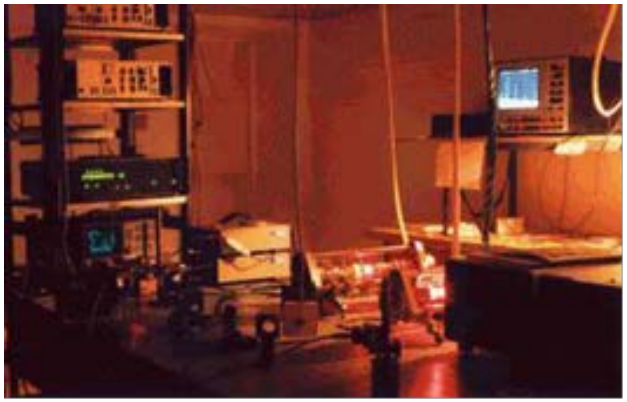
Ultraviolet comb



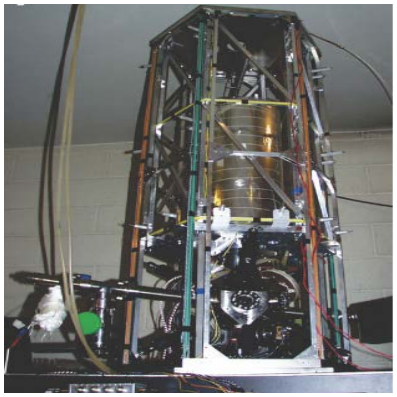
Fundamental constant measurement



Optical frequency links



ranging



Primary frequency standard

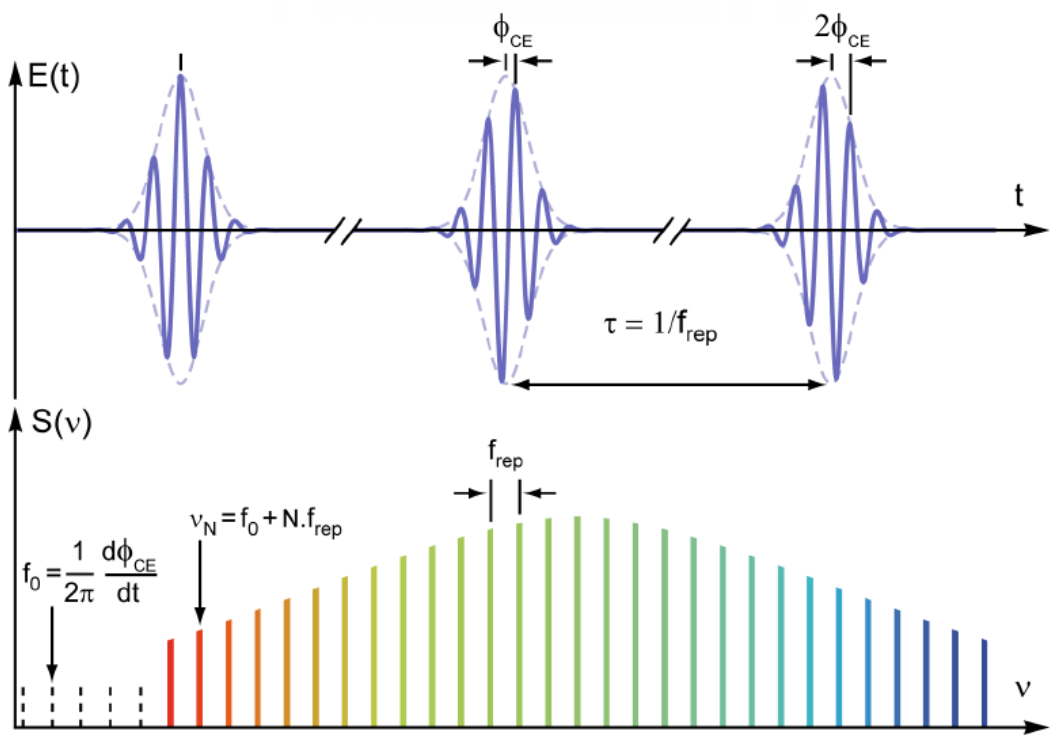
What is the optical frequency comb?

Optical frequency comb is a frequency controlled femtosecond mode-locked laser.

Two steps forward a comb.

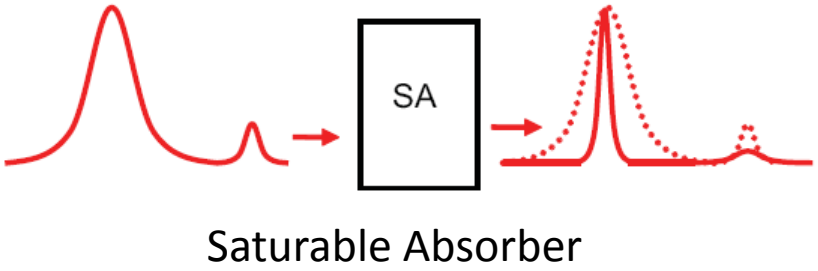
1. Femtosecond mode-locked laser
   - Ti: sapphire (lowest noise)
   - Er:fiber (best robustness)
   - Yb:fiber (good power conversion)

2. Control of comb`s frequencies:
   - repetition rate (f_r)
   - Carrier envelope offset frequency (f_{ceo})

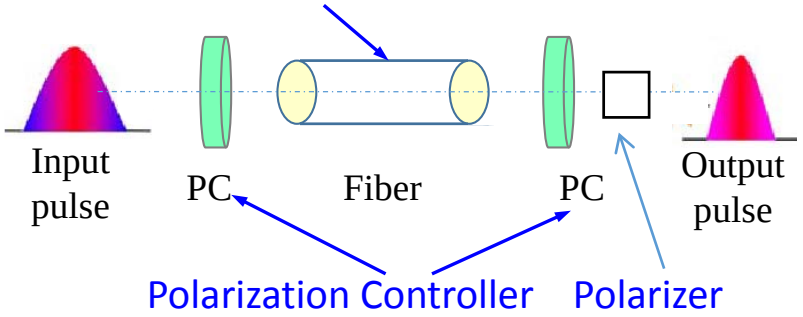


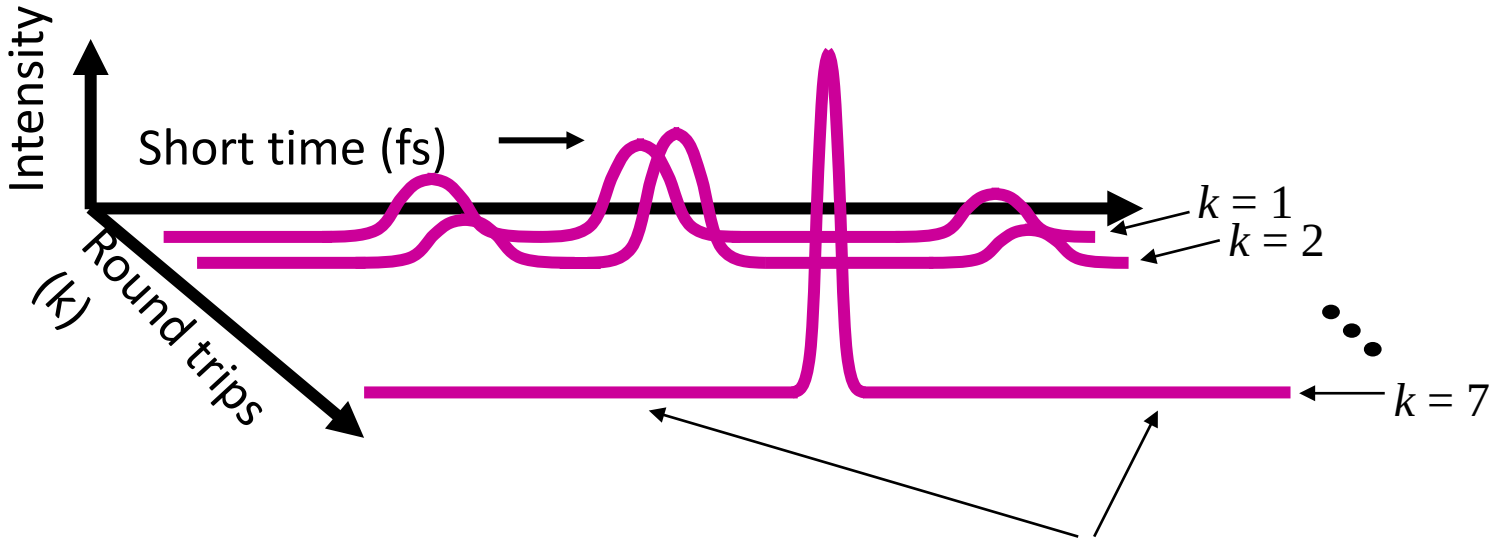
Mode-locking mechanism

NPR ~ nonlinear polarization rotation, a passive mode-locking technique



Intensity-dependent rotation of light

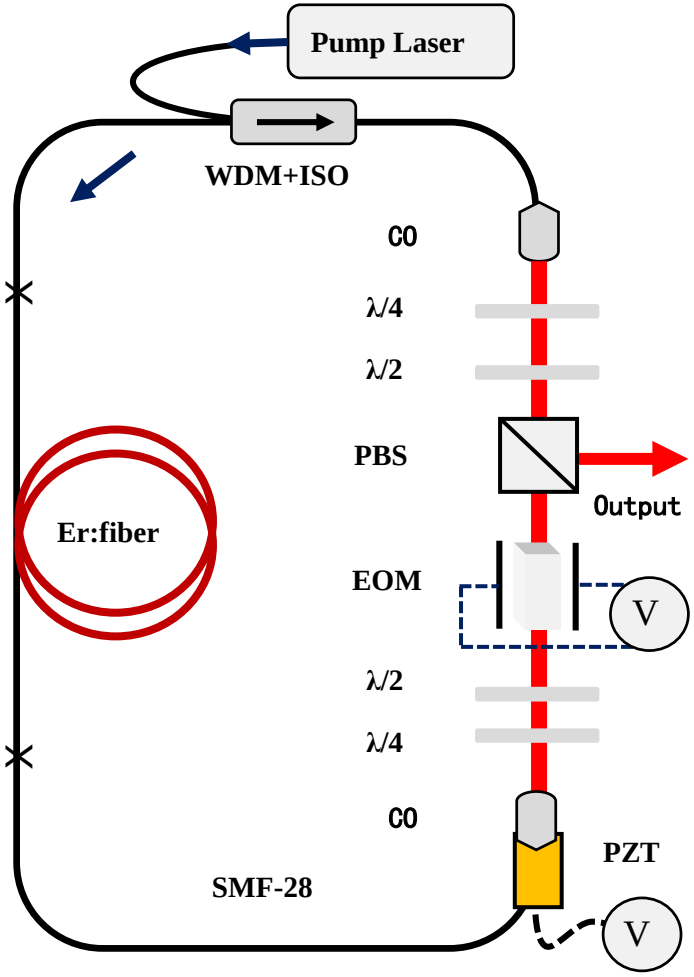




Notice that the weak pulses are suppressed, and the strong pulse shortens and is amplified.

NPR Er:fiber optical frequency comb

NPR ~ nonlinear polarization rotation, a passive mode-locking technique



Kerr effect -> NPR

NPR + Polarization selection= SA

Pump Laser： 976nm， Power~1W；

WDM： Wavelength Division Multiplexer；

Er:fiber： Liekki ER110, ~44cm；

SMF-28： 34cm,；

EOM： $LiNbO_3$**, 8mm；**

PZT： Piezotransducer， 20mm；

Net dispersion ~ -2000 fs²；

NPR Er:fiber optical frequency comb

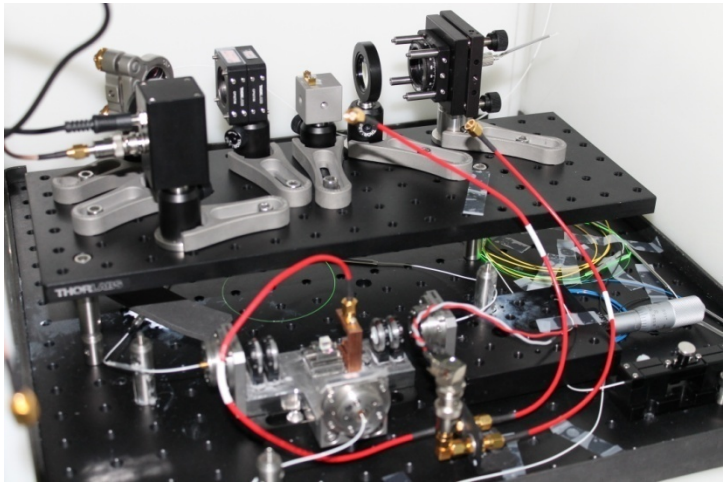
NPR ~ nonlinear polarization rotation, a passive mode-locking technique

Output power: ~180 mW (η ~ 18%);

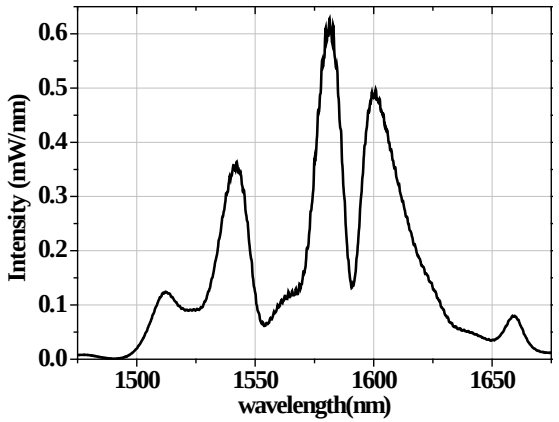
10 dB bandwidth: ~ 130 nm;

Repetition rate: ~ 232 MHz;

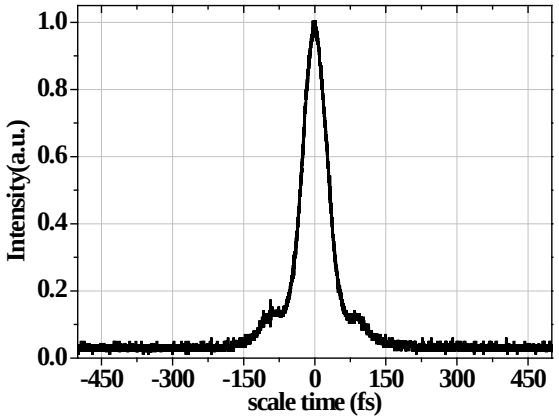
Pulse duration: ~ 60 fs;



Peak power is more than 10 kW



Optical spectrum



Autocorrelation

Hybride Er:fiber optical frequency comb

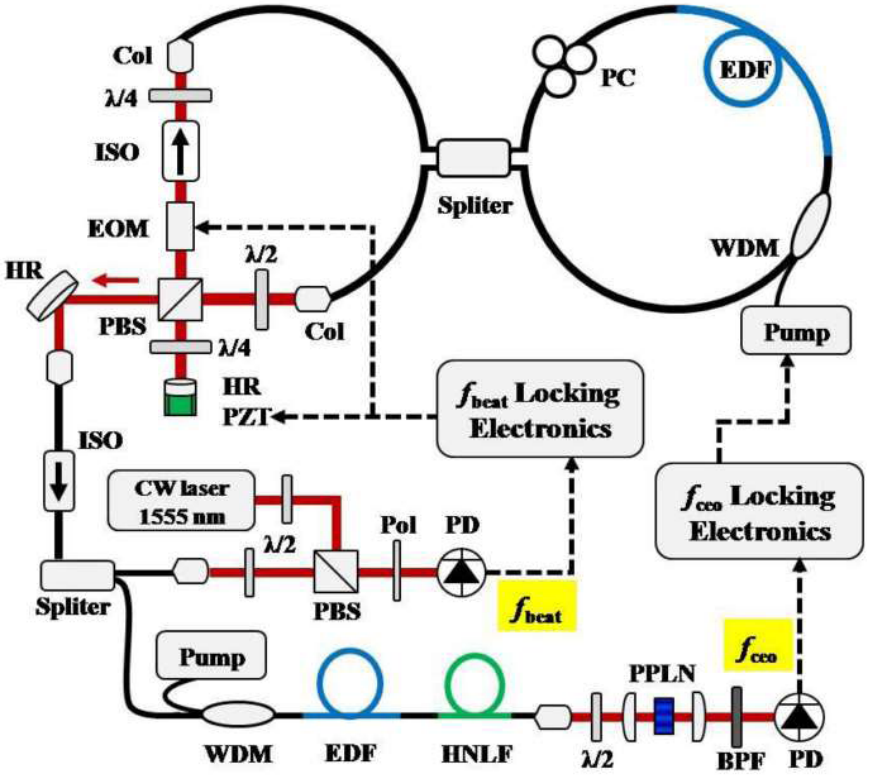
Reliability of optical frequency combs is also importance for applications.

NPR (left, low noise) +

NALM (right, robust)

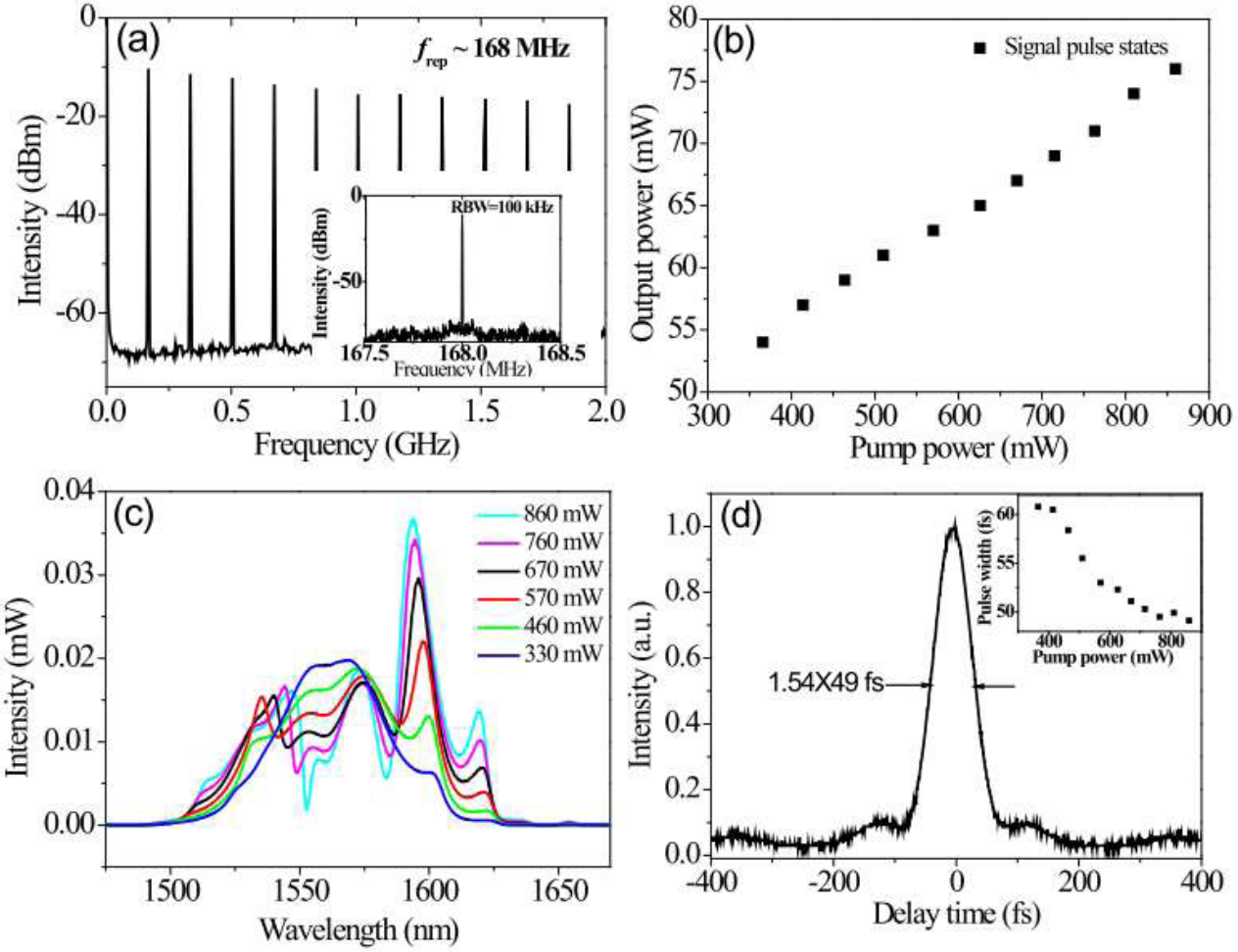
= Hybride fs laser (Self-start)

- Self-start mode-locking;
- Large polarization tuning dynamic range;
- Large power tuning dynamic range.
- Broadband frequency control.

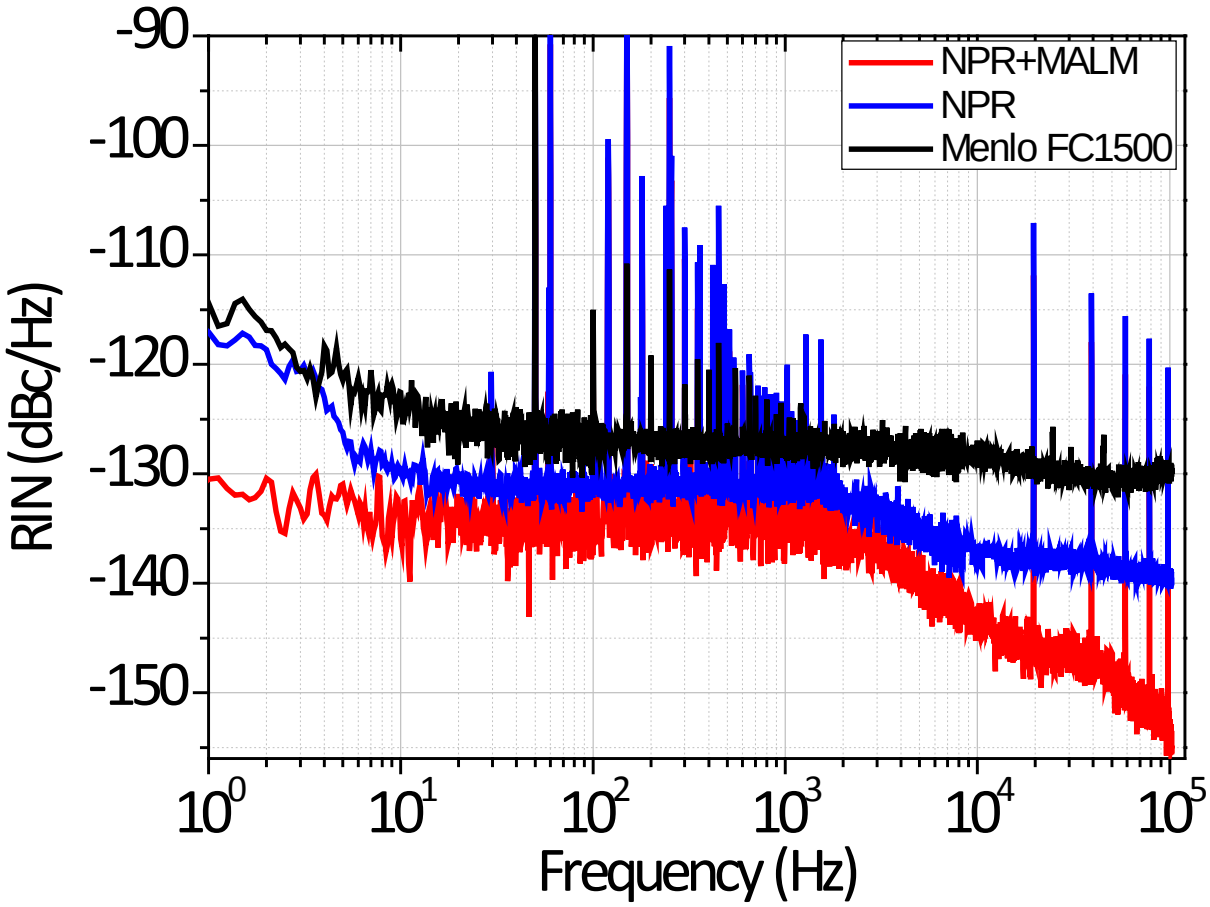


Y. Zhang, *et al.* (2017). "Robust optical-frequency-comb based on the hybrid mode-locked Er:fiber femtosecond laser." *Optics Express* **25(18): 21719-21725.**

Hybride Er:fiber optical frequency comb



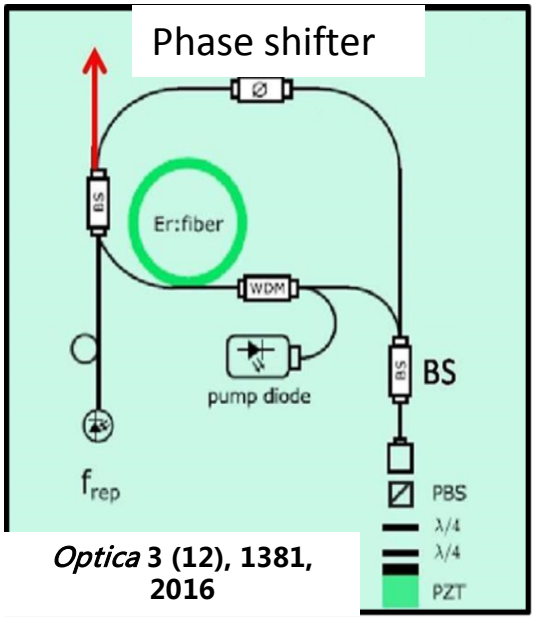
Hybride Er:fiber optical frequency comb



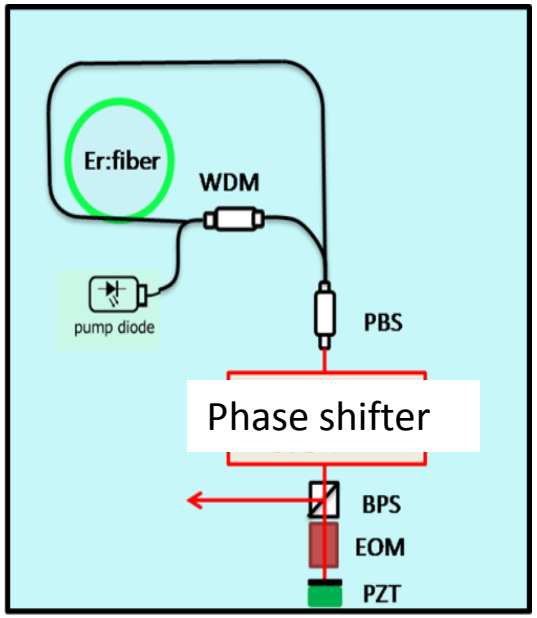
Laser Journal of China 41(8)，0802004, 2014; Opt. Exp. 25, 21719, 2017

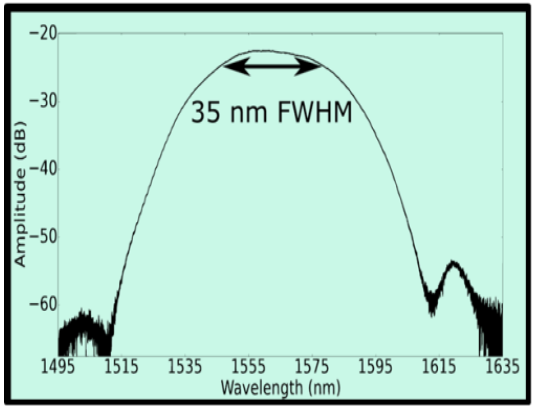
Figure-9 mode-locked laser

Full PM fiber mode-locked laser (Figure-9)

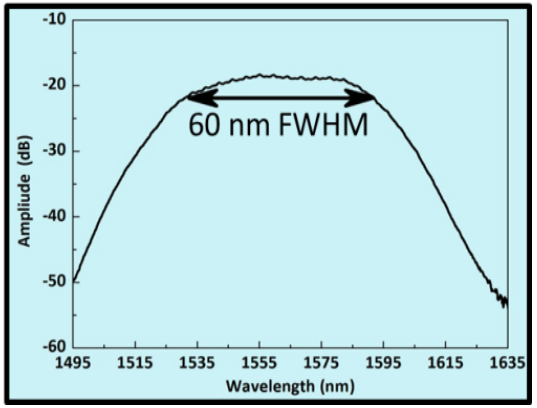


Optica 3 (12), 1381, 2016





Menlo system Inc.



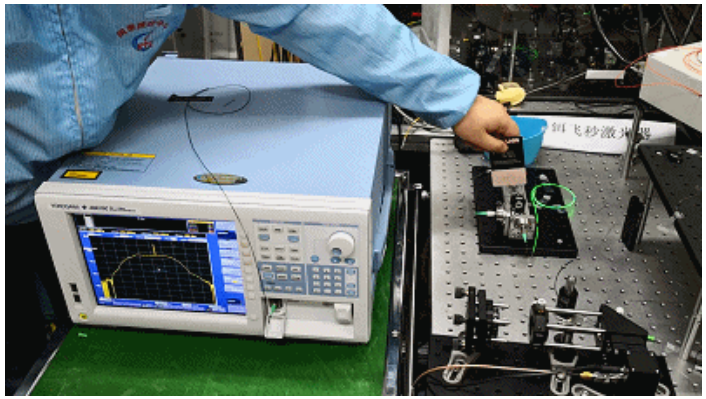
NTSC

Nonlinear amplification loop mirror (NALM) mode-locking mechanism

Sagnac Interferometer + kerr effect

➡ **Turn-key system**

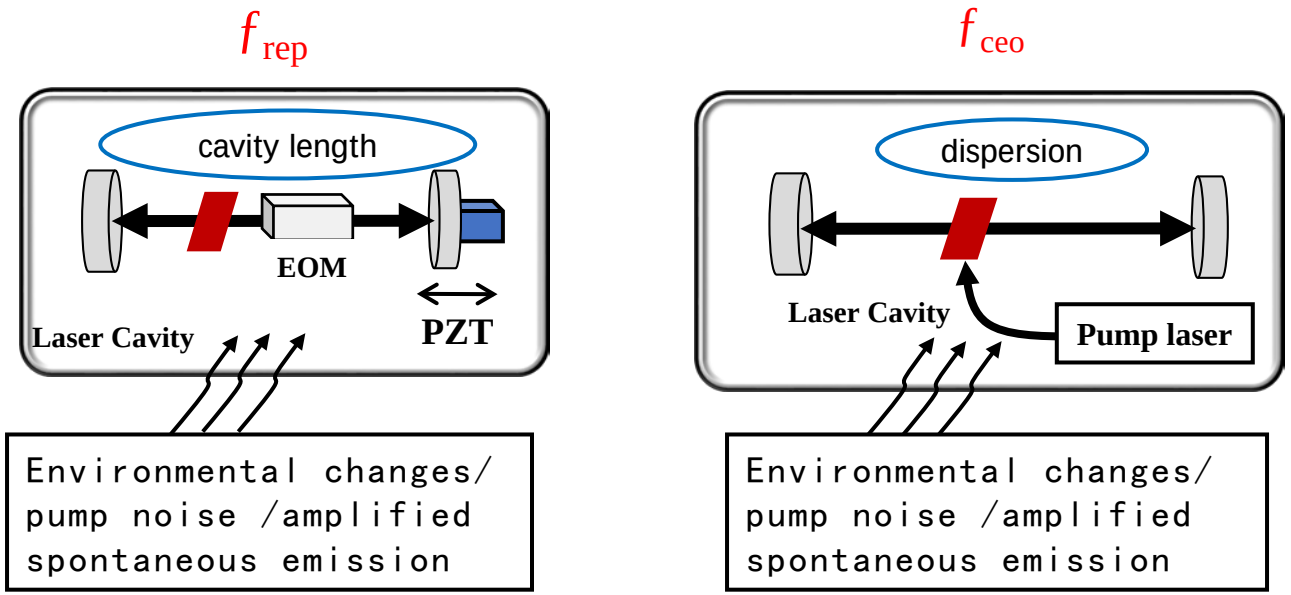
Suitable for space application!



Frequency control of OFC

■ Frequency control

- ✓ broad bandwidth ⟶ tight phase lock with less residual noise
- ✓ large range ⟶ long term phase lock

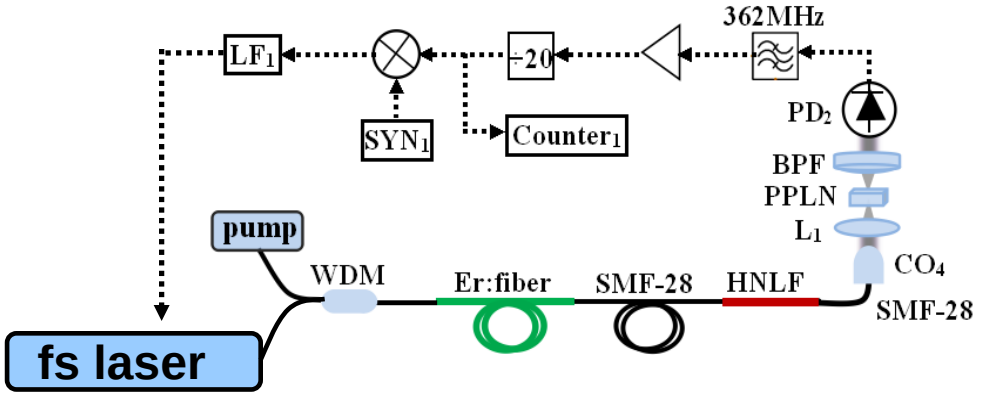


repetition rate determined by laser cavity length

offset frequency dependent on dispersion in the laser cavity

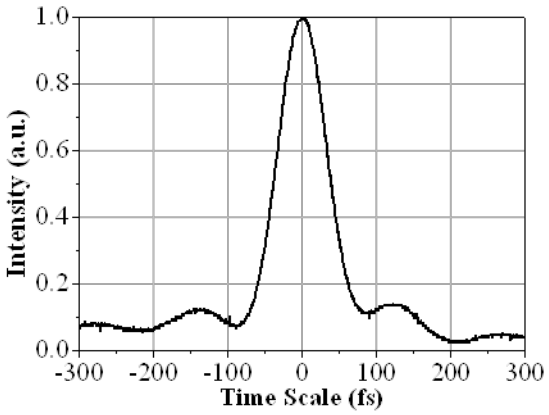
f_{ceo} detection and control

Signal to noise ratio of f_{ceo} is a limitation of Robustness of optical combs



$\nu_N = f_{ceo} + N f_r$

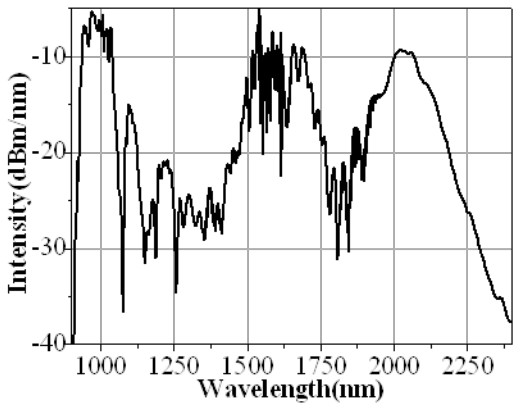
~50 fs



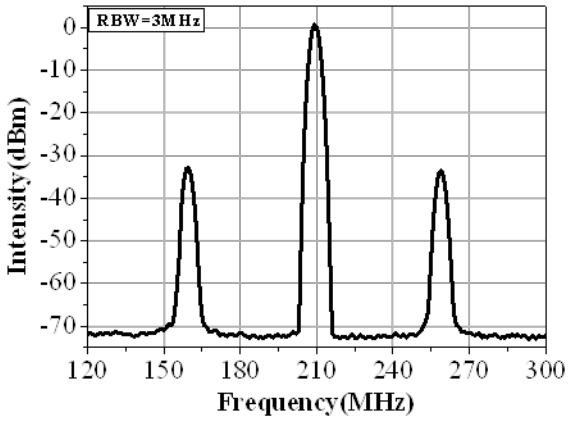
2n f_r+f_{ceo}

n f_r+f_{ceo}

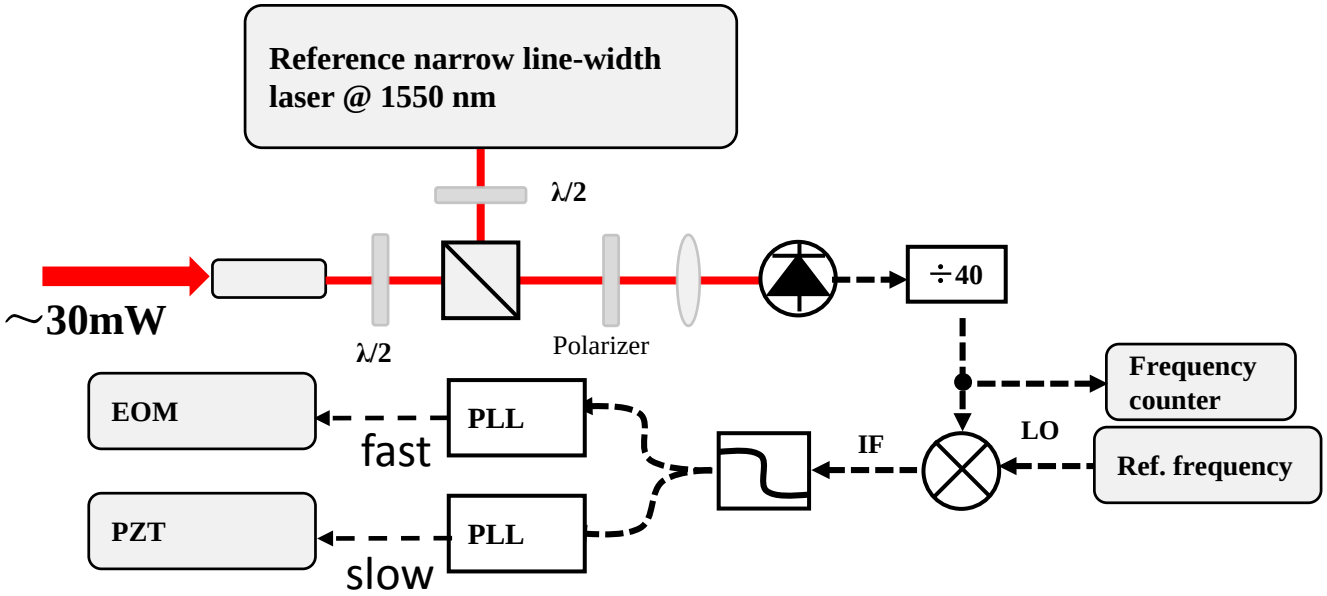
2n f_r+2f_{ceo}

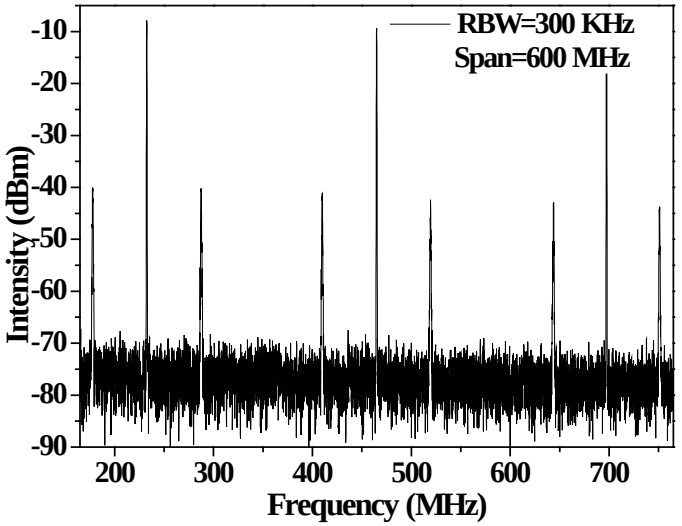


3MHz res. 40dB



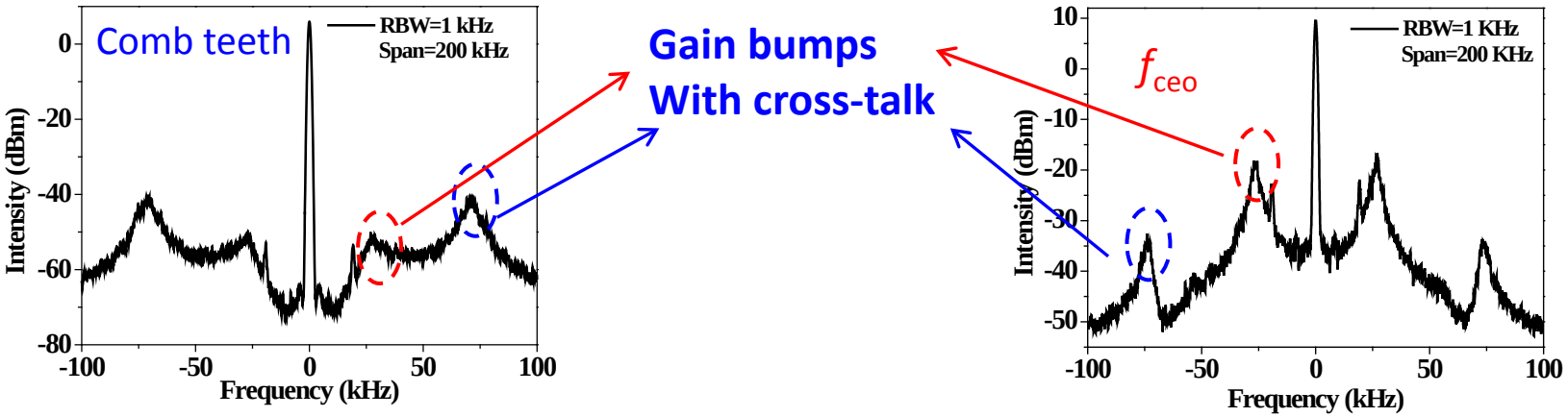
Repetition rate control





Results of frequency control

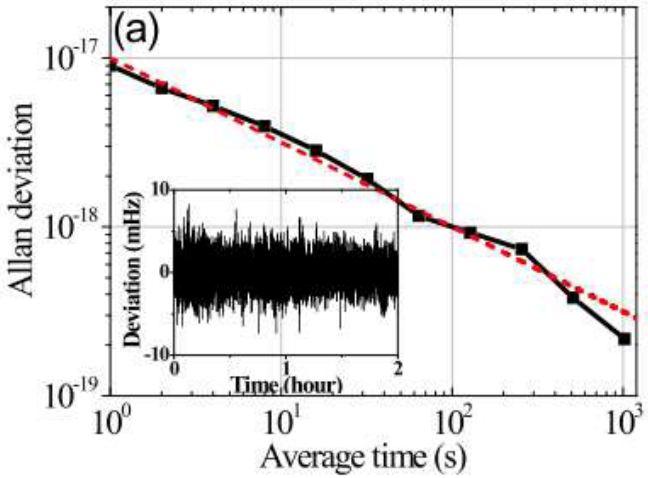
Evaluation of frequency control ability

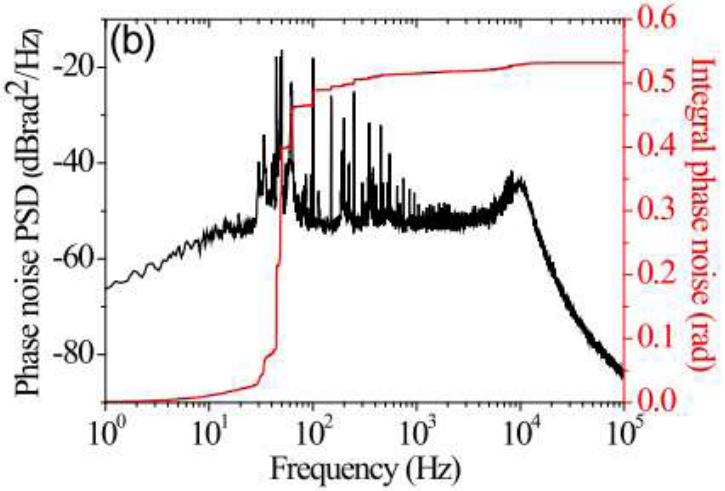


A comb teeth and f_{ceo} are frequency stabilized simultaneously

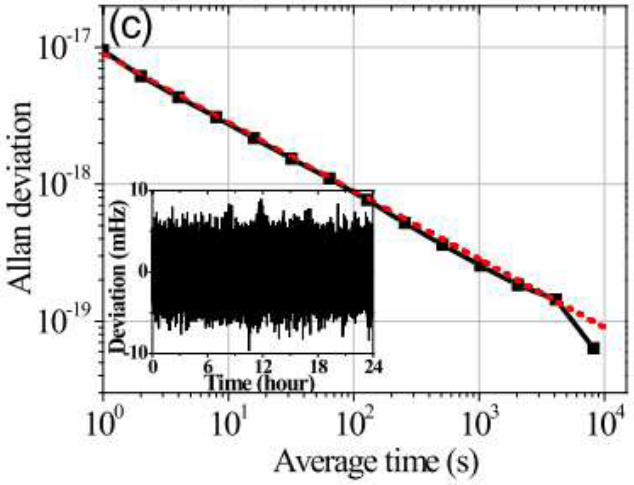
Results of frequency control

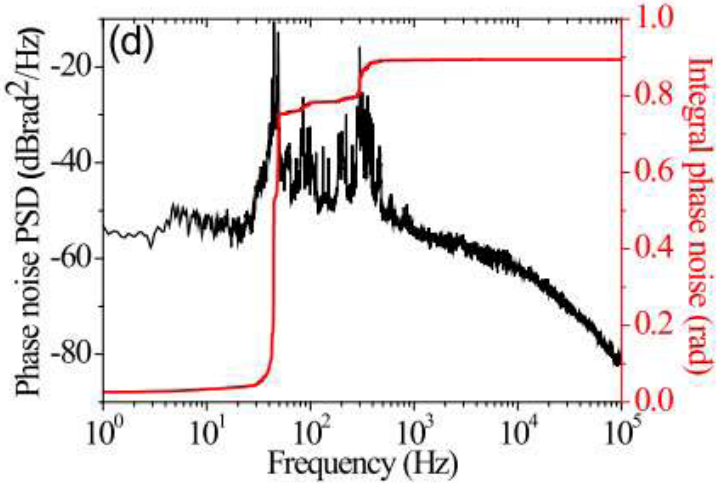
f_{ceo}





f_r

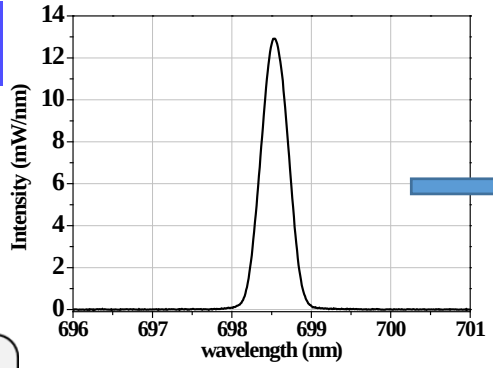


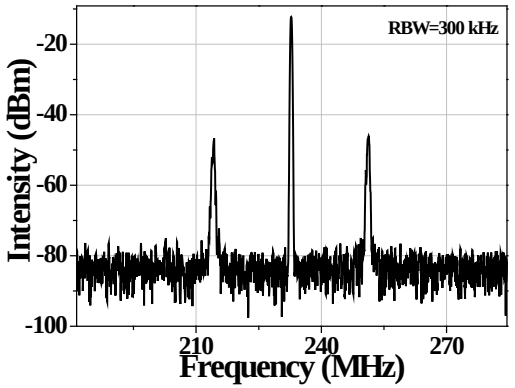


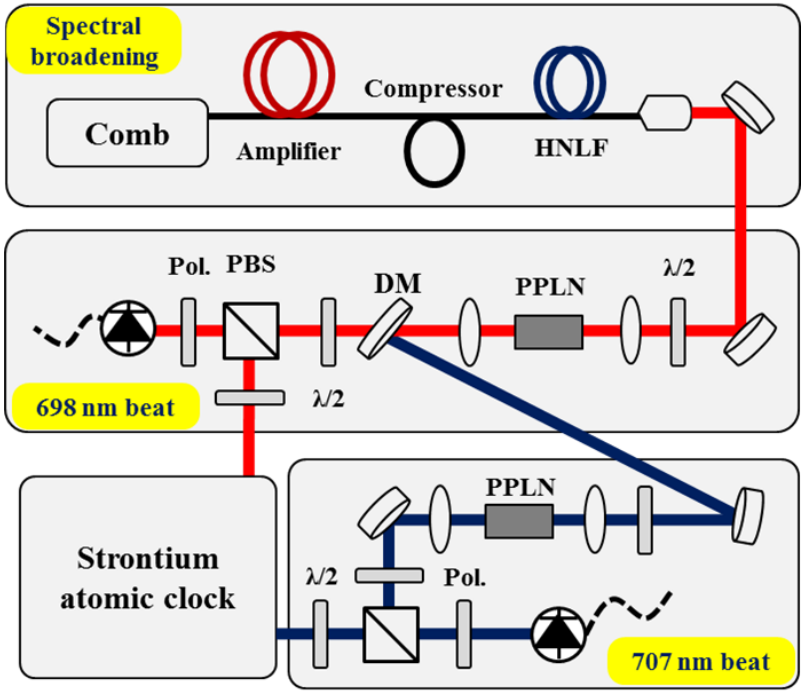
Applications of our comb systems

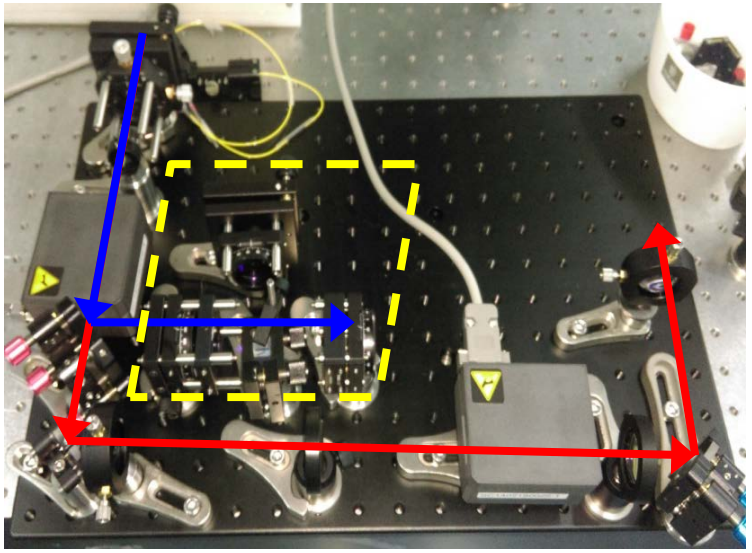
Sr Optical clock @ NTSC

~ 1 μW/mode @ 698 nm





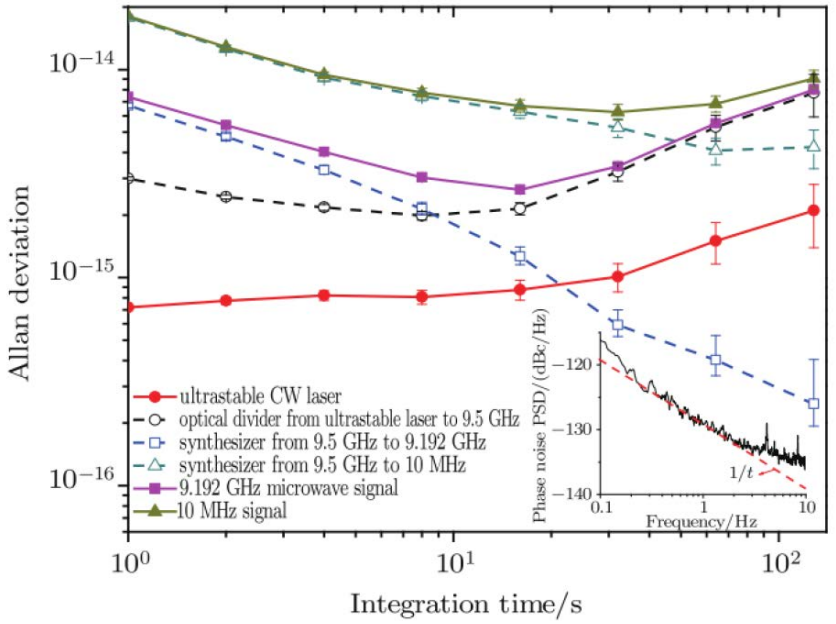


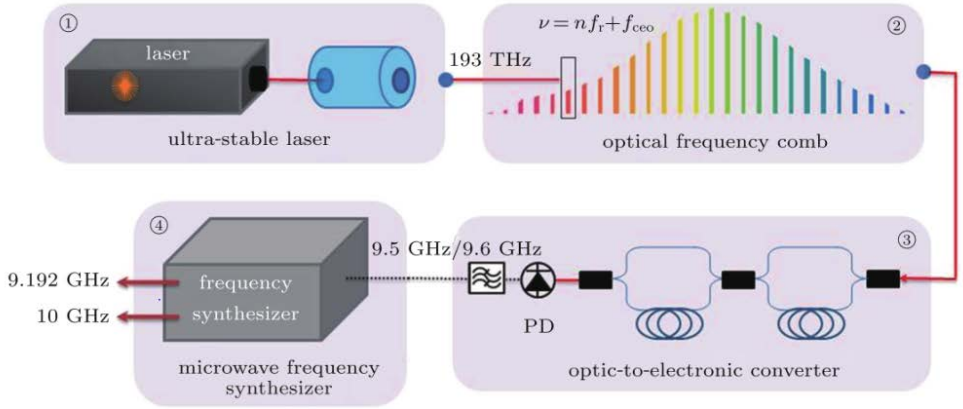


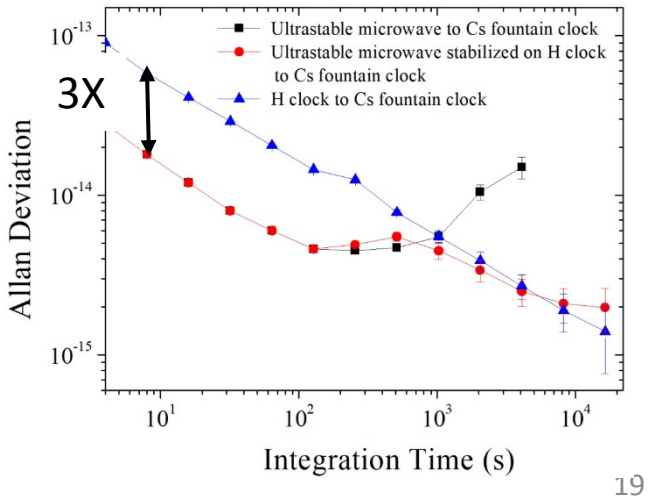
Y. Zhang， L. Yan， H. Jiang， S. Zhang, Journal of time and frequency， 40(3), 2017

Applications of our comb systems

Ultra stable photonic microwave generator







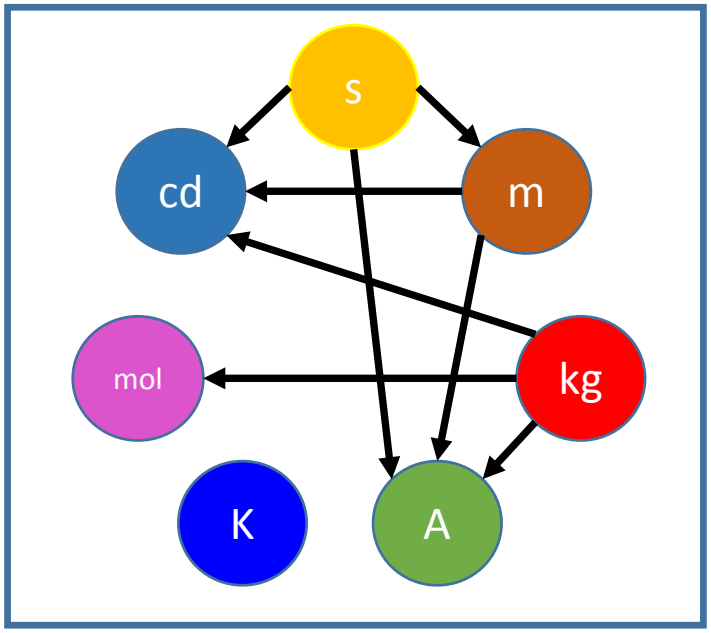
Thank you for your attention!

The end!

News for metrology

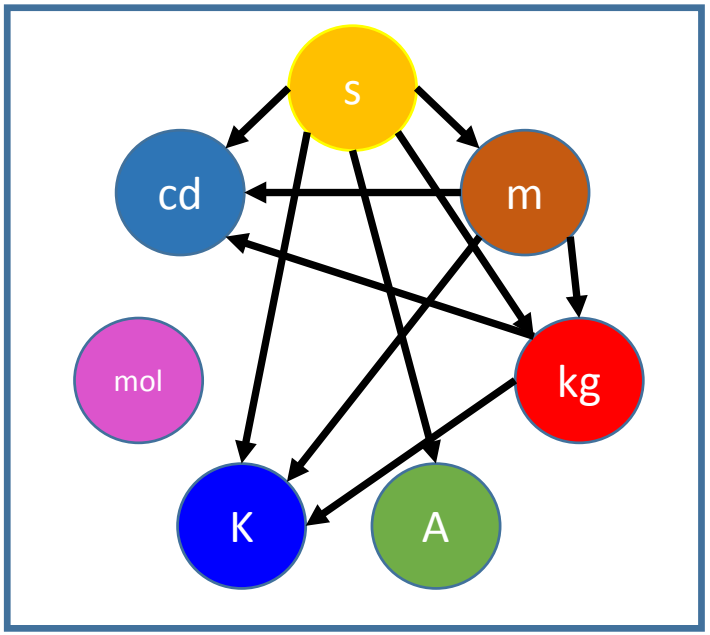
The International System of Units (SI)

Up to last month



Definition of the meter, the ampere and the candela depend on the definition of the second

From 20th May 2019



All definitions except that of the mole depend on the definition of the second

“Never measure anything but frequency”

Arthur L. Schawlow winner of the 1981

Nobel Prize for Physics

Quoted by Theodor W. Hansch in his

2005 Nobel Prize Lecture