上海交通大学
SHANGHAI JIAO TONG UNIVERSITY

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Kunming, China
SJTU

Optical time and frequency transfer over fiber and free-space links

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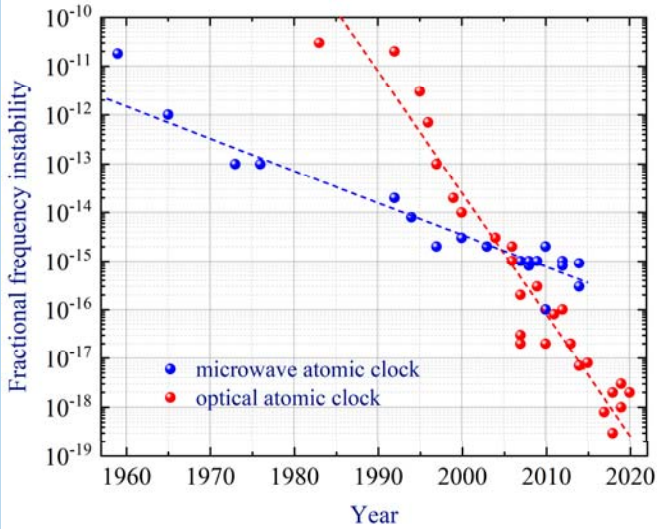
饮 水 思 源 • 爱 国 荣 校

Content

Background

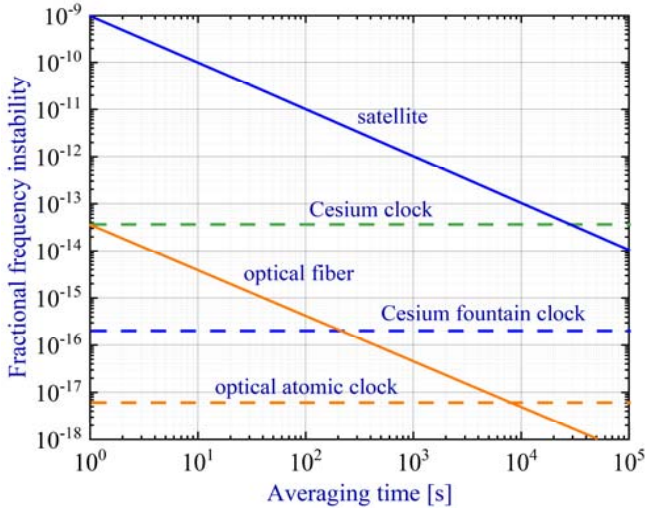
- Time: One of the seven International System (SI) of units with the highest measurement accuracy
- Precise time and frequency have important applications in cutting-edge scientific research, communications, national defense and other fields

Atomic/Optical clock

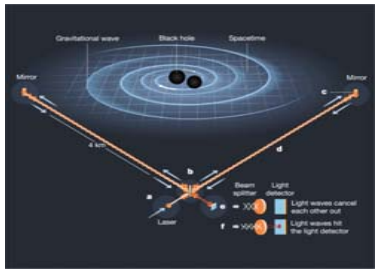


- The stability and accuracy of microwave/optical atomic clocks continue to improve.

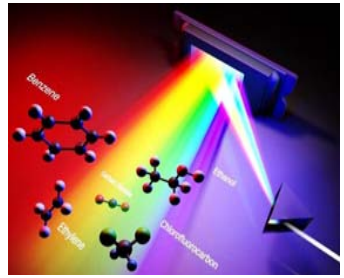
Time-frequency transfer



- Optical fiber is the best transmission medium for ground-based time-frequency transfer systems.



Cutting-edge scientific research

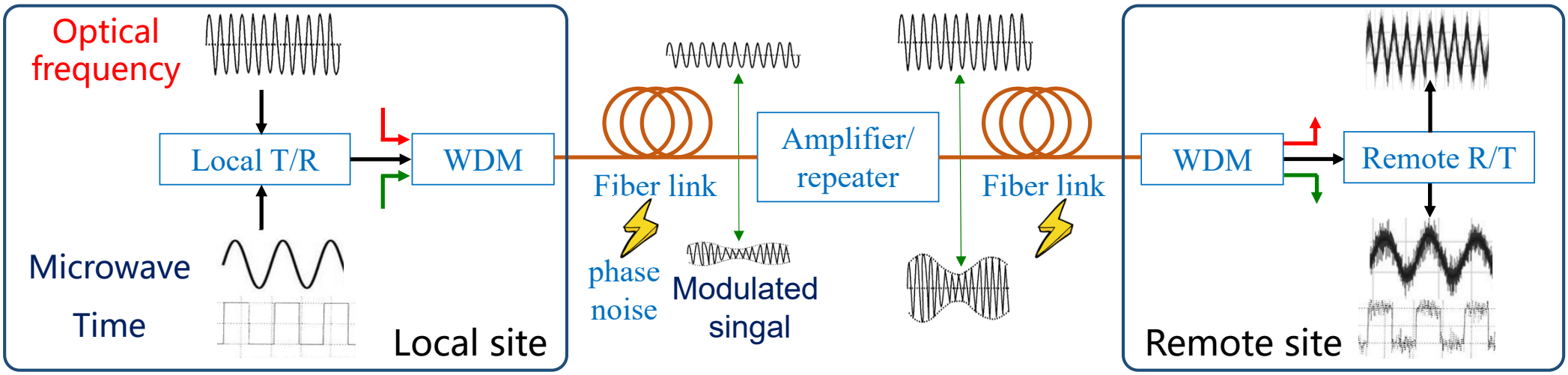


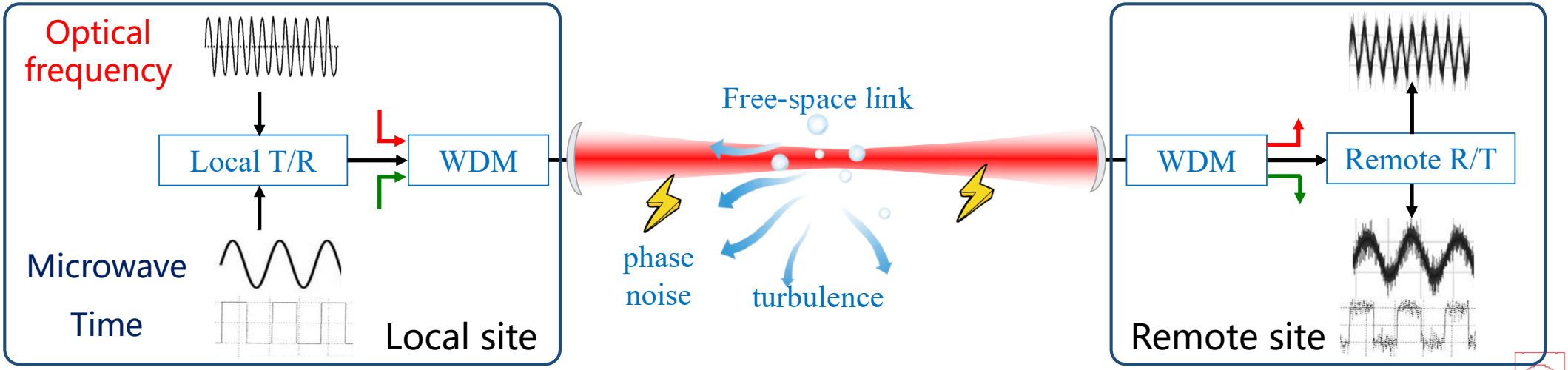
Spectroscopy

Communications

Navigation

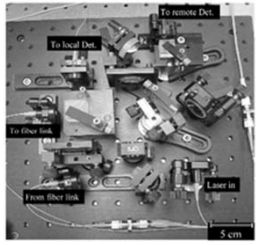
Principle of optical time-frequency transfer





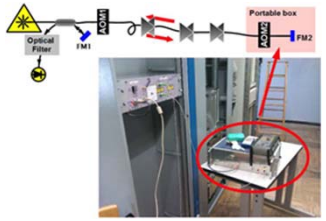
Research progress (Fiber link)

Ma (NIST)
25 m
1994



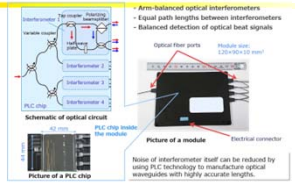
Newbury (NIST)
251 km
6×10^{-19}/100 s
2007

Predehl (MPQ&PTB)
1840 km
4×10^{-19}/2000 s
2012



Calonico (INRIM)
1284 km
3×10^{-19}/1000 s
2012

Cantin (LNE-SYRTE)
1480 km
2×10^{-20}/8000 s
2015



Akatsuka (NTT)
240 km
1×10^{-18}/2600 s
2020

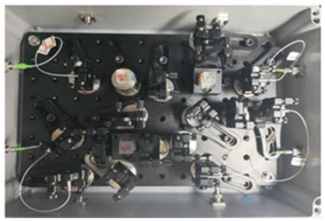
Schioppo (NPL)
2220 km
7×10^{-17}/200 s
2022

2015
ECNU
82 km
4×10^{-19}/10000 s

2016
NTSC
112 km
4×10^{-20}/10000 s

2018
SIOM
180 km
1×10^{-20}/20000 s

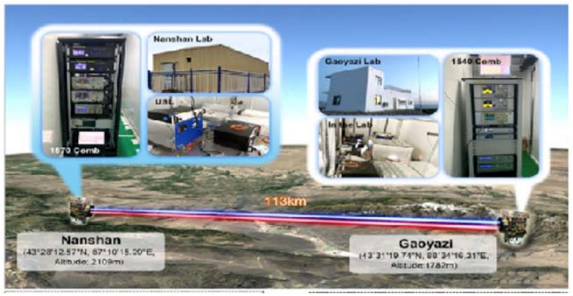
2020
SJTU
145 km
2×10^{-19}/10000 s

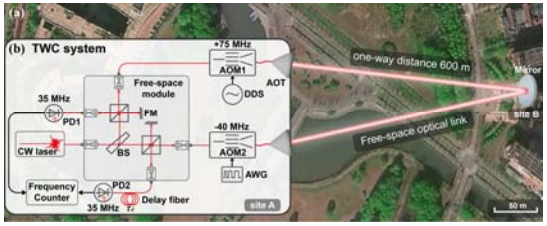


2022
NTSC
490 km
3.7×10^{-19}/10000 s

2023
SJTU
1210 km
1.2×10^{-19}/10000 s

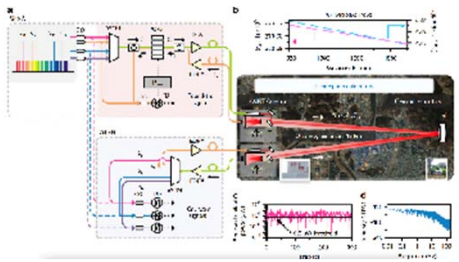
Research progress (Free-space link)





Qiu (SJTU)

Optical carrier
1.2 km
4.6×10^{-19}/ 1000 s

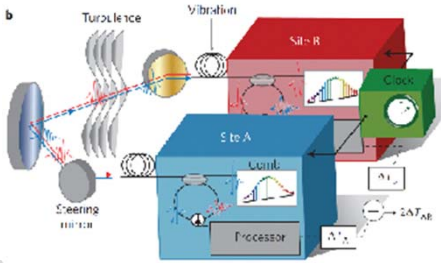


Shen (USTC)

Frequency comb
113 km
4×10^{-19}/ 10000 s

Kang (KAIST)

Optical carrier
18 km
3.99×10^{-16}/ 0.1 s



Chen (USTC)

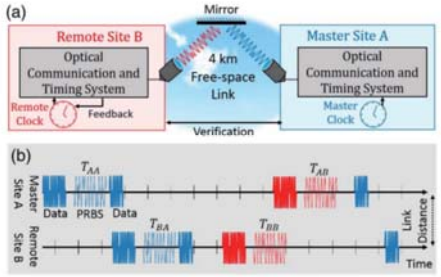
Microwave modulation
110 m
2×10^{-16}/ 1000 s

Chen (SIOM)

Microwave modulation
124 m
3.2×10^{-17}/ 1000 s

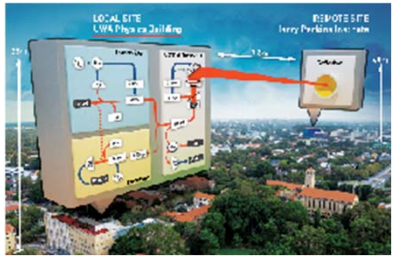
Khader (NIST)

Time PRBS modulation
4 km
16 ps/ 8 h



Gozzard (UWA)

Optical carrier
2.4 km
6.1×10^{-21}/ 300 s

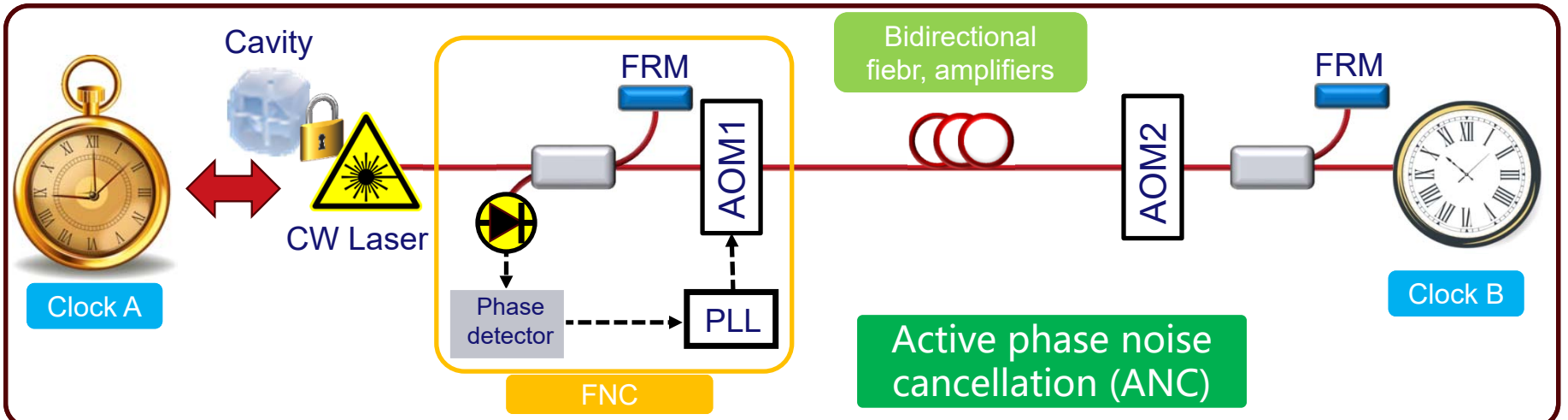


Emily (NIST)

Frequency comb
300 km
$2.8\times10^{-15}\tau^{-3/2}$

Content

Challenges of optical frequency transfer



① In-loop phase noise detection and cancellation

- Large phase detection range and cancellation bandwidth
- Strong environmental adaptability and high robustness

② Out-of-loop phase noise suppression

- Avoid precision temperature control and length matching
- Peal-time measurement and compensation

③ Cycle-slip measurement and compensation

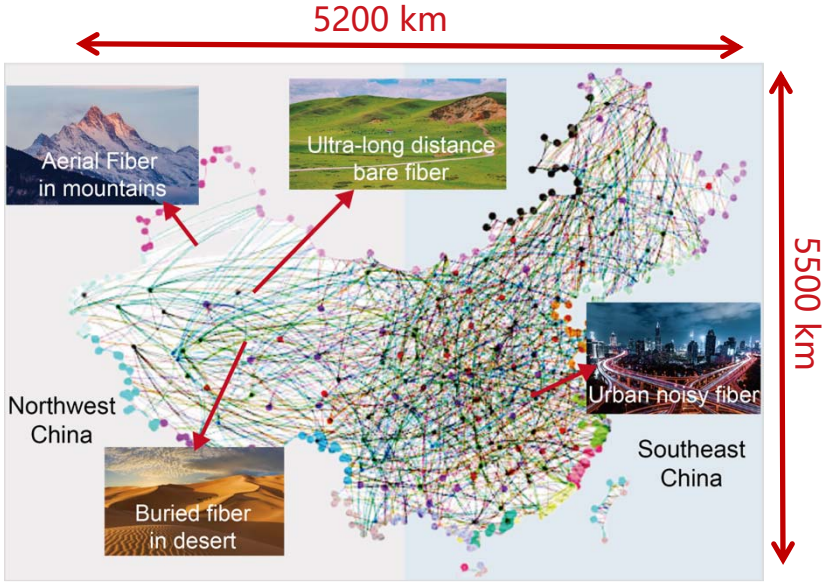
- Real-time measurement and compensation method
- Software algorithms (Kalman filtering, deep learning, etc.)

① In-loop phase noise detection and cancellation

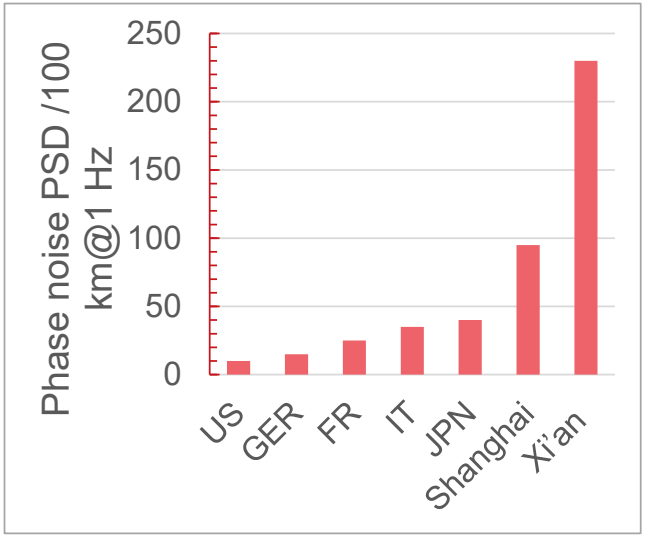
- Phase noise suppression capability

$$S_{residual}(\omega) = \frac{1}{3}(\omega\tau_0)^2 S_{link}(\omega)$$

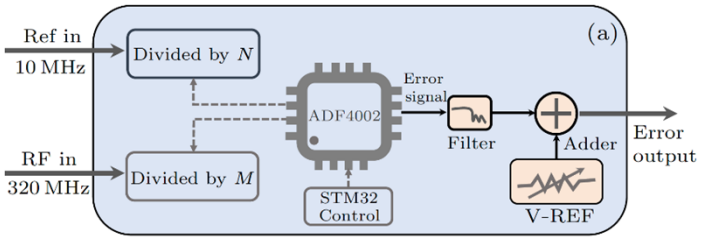
Link delay

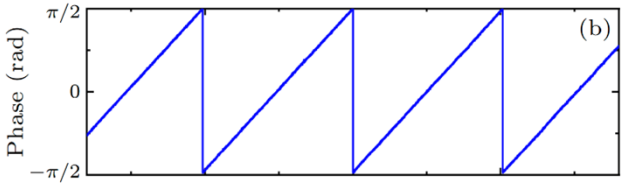


Fiber networks in China

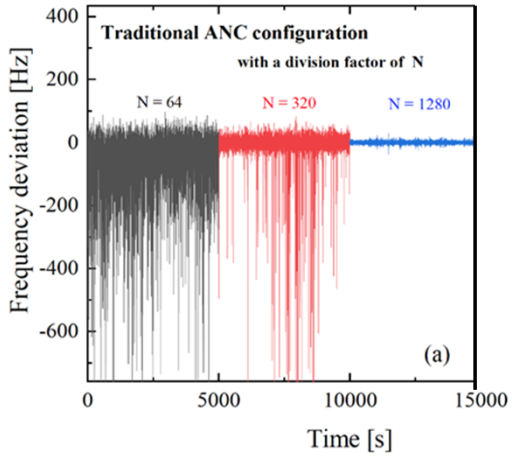


Fiber-introduced phase noise

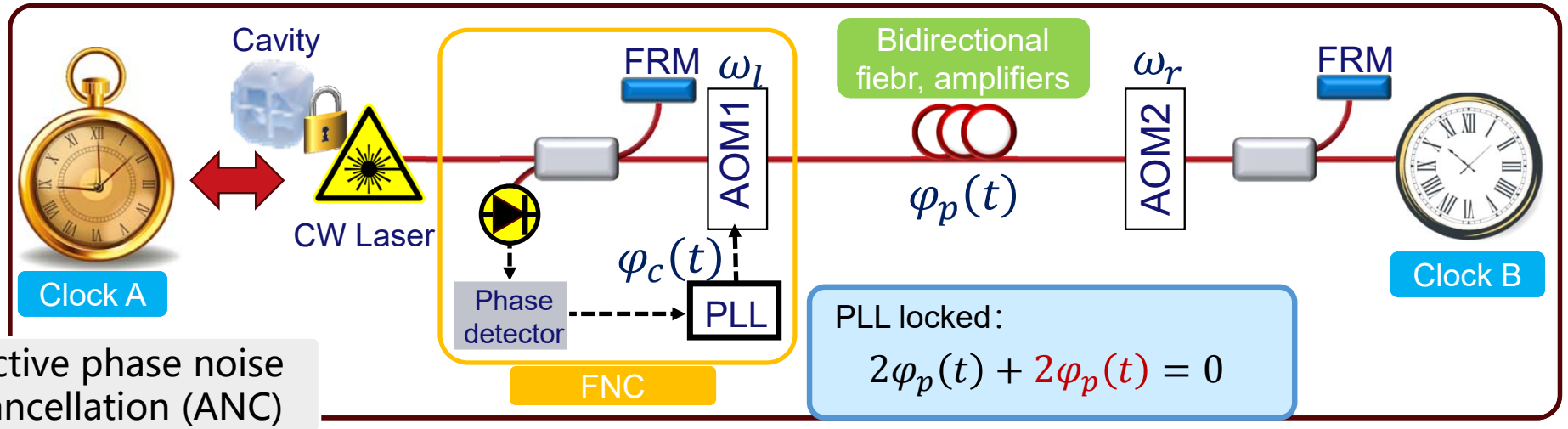




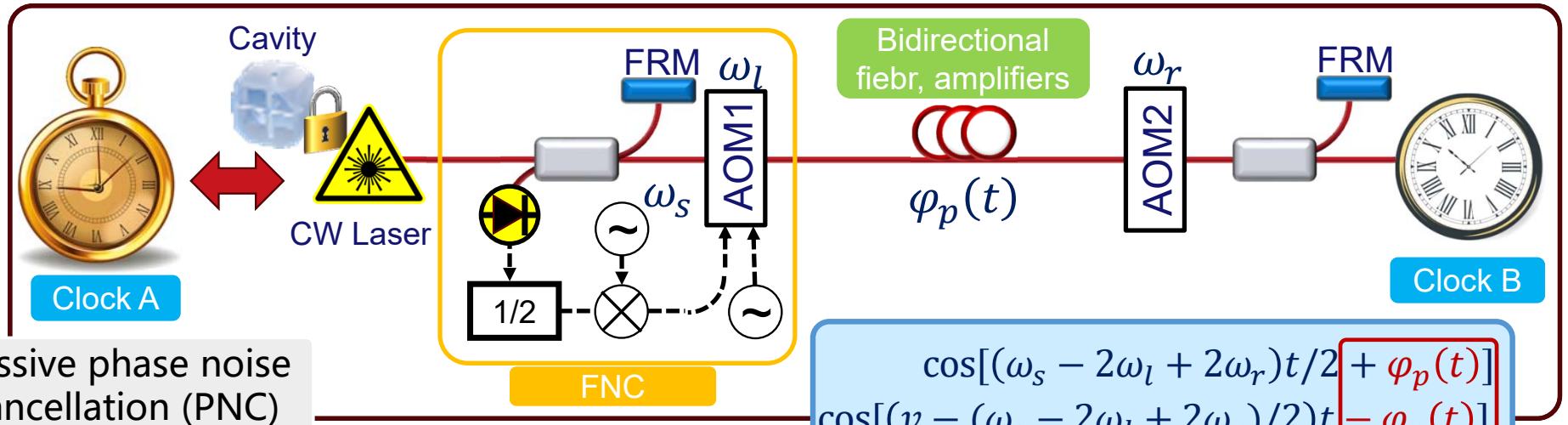
Analog phase detector



① In-loop phase noise detection and cancellation



Active phase noise cancellation (ANC)

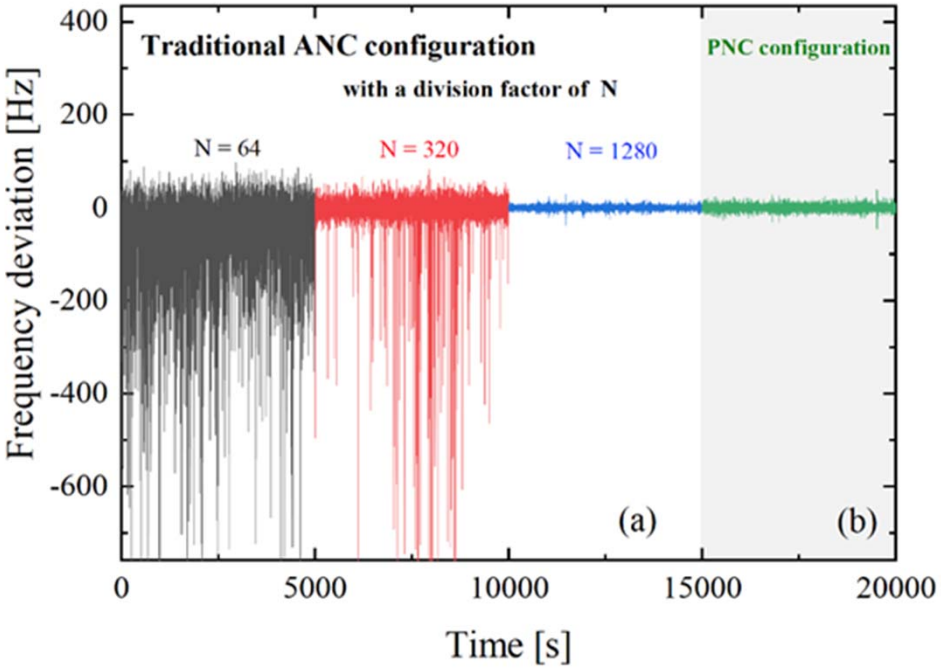


Passive phase noise cancellation (PNC)

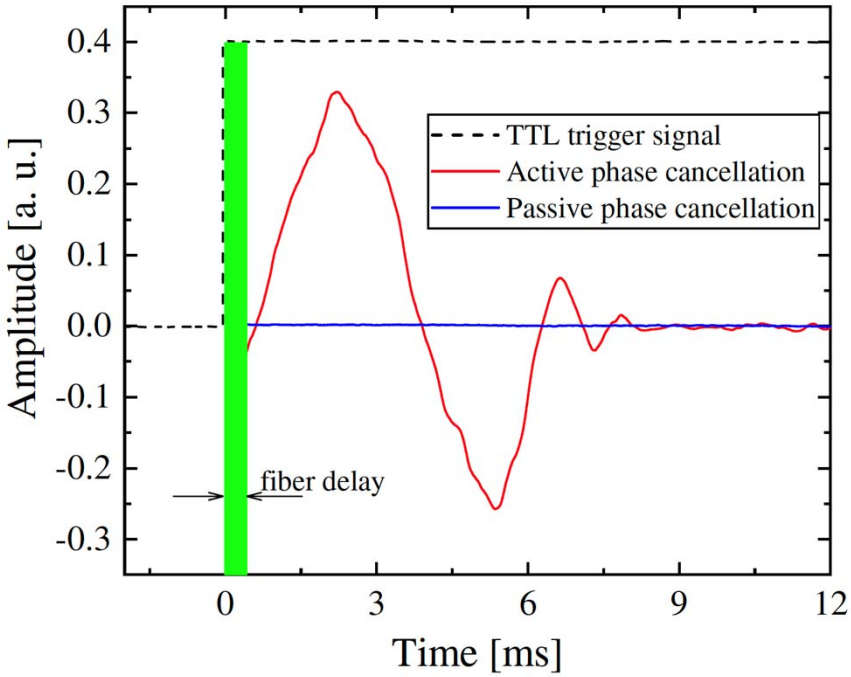
L. Hu, et al., Passive optical phase noise cancellation, 45(15), 4308-4311, 2020

① In-loop phase noise detection and cancellation

- Passive phase noise cancellation (PNC)
  - ☺ No need for large dynamic phase detection and complex servo control
  - ☺ Large dynamic range and fast compensation speed



PNC with large dynamic range



Compensation speed comparison

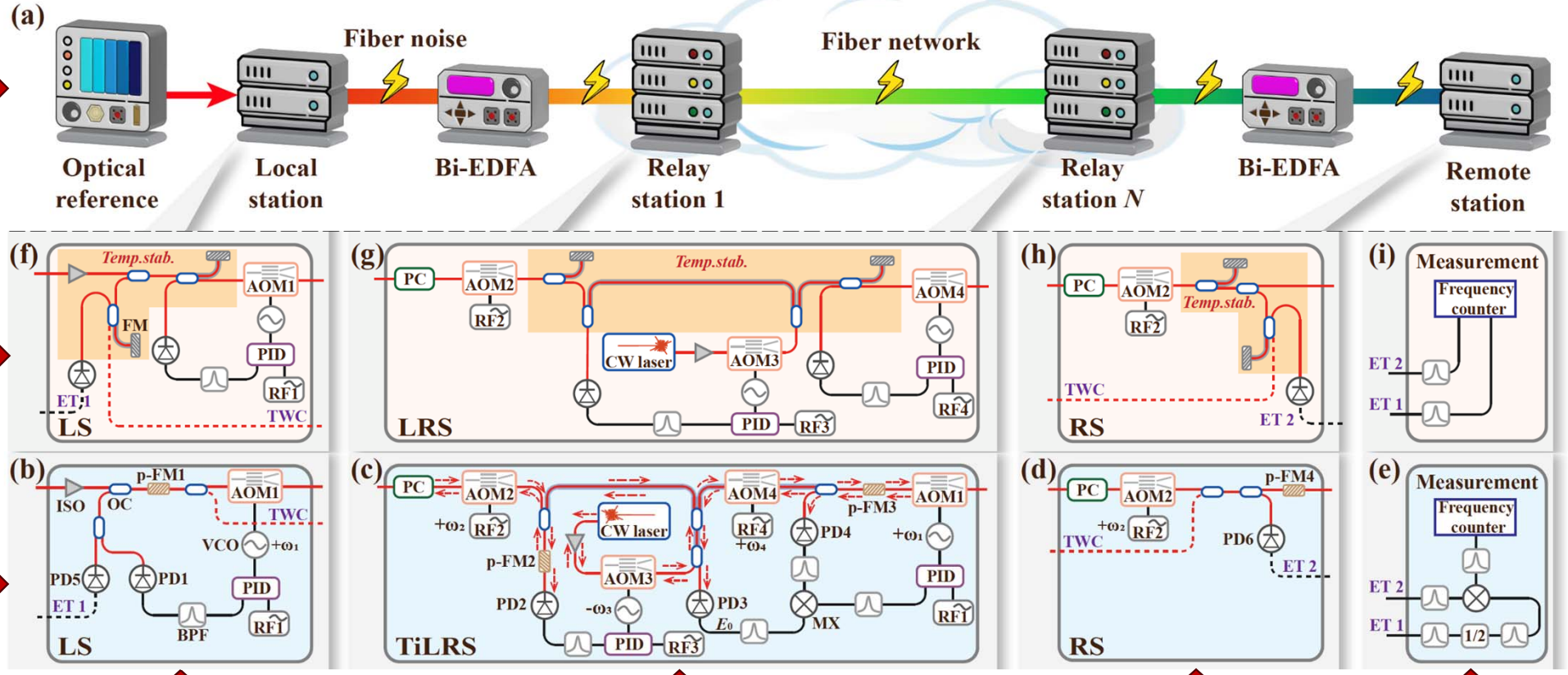
② Out-of-loop phase noise suppression

$$\Delta f = 2\pi f_0 \frac{\Delta l}{c}(\alpha_n + n\alpha_\Lambda)\frac{\Delta T(t)}{\Delta t}$$ ➡ 1 cm path length error (1 ° C@3600s) ➡ 1E-19/1800s (Allen deviation)

Cascaded system architecture

Traditional method

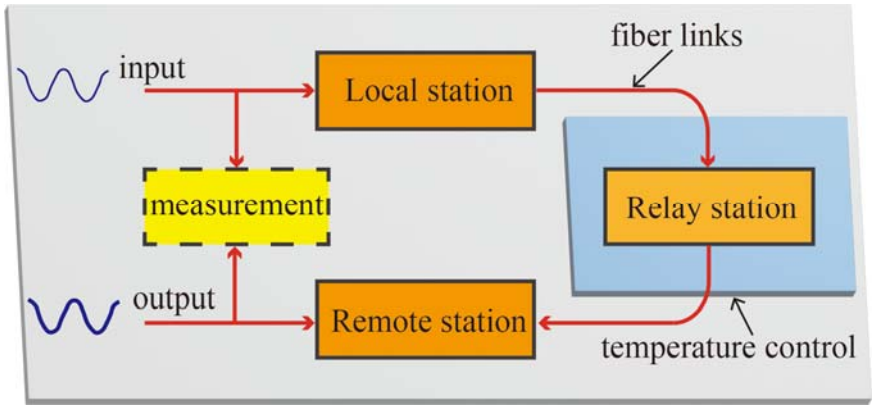
Novel method



Local site | Laser repeater station | Remote site | Test method

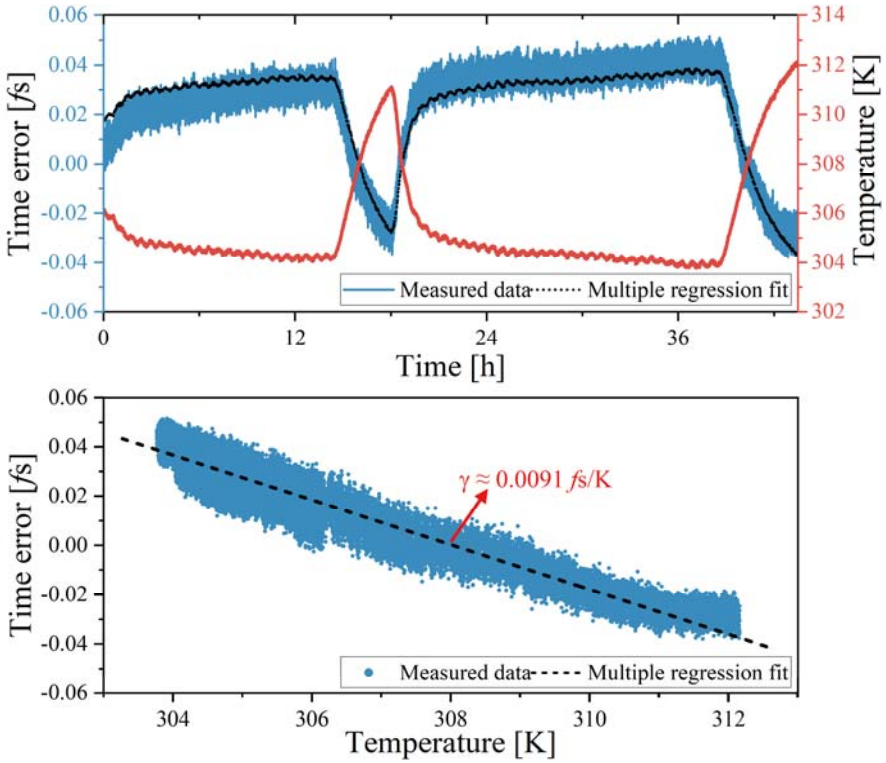
② Out-of-loop phase noise suppression

❑ Temperature coefficient test results



Measurement system

No	Organization (Method)	Coefficient
1	France (fiber optic, active + passive temperature control)	1 fs/K
2	Germany, US (Free space optical devices)	1.86 fs/K
3	SJTU (fiber optic, no control)	9 as/K

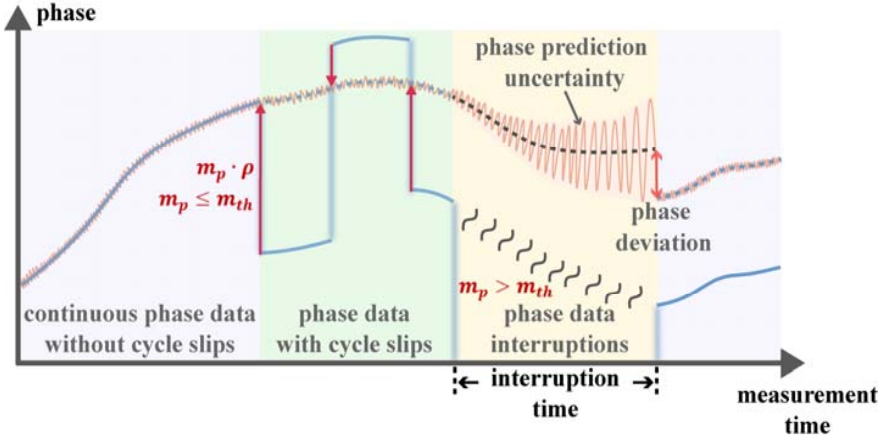


Temperature coefficient measured results

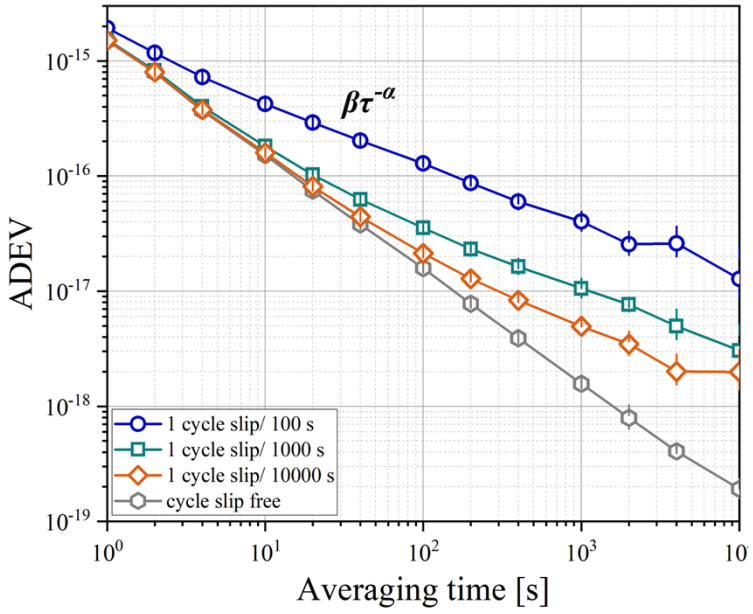
Extremely low temperature coefficient (9 as/K)

③ Cycle-slip measurement and compensation

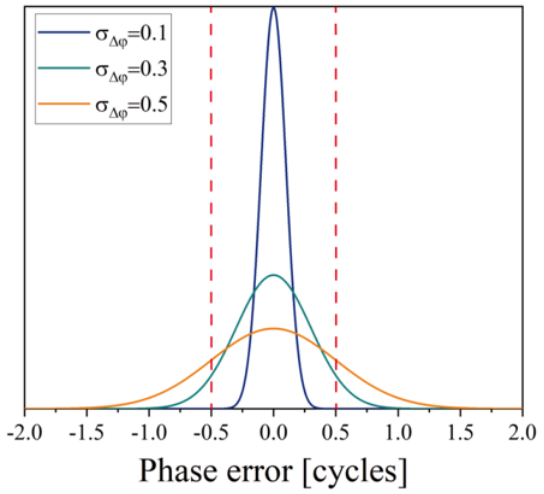
- Optical carrier-based phase measurement
  - ☺ High precision (1550nm~5 fs)
  - ☹ Existing cycle ambiguity ➡ cycle slips

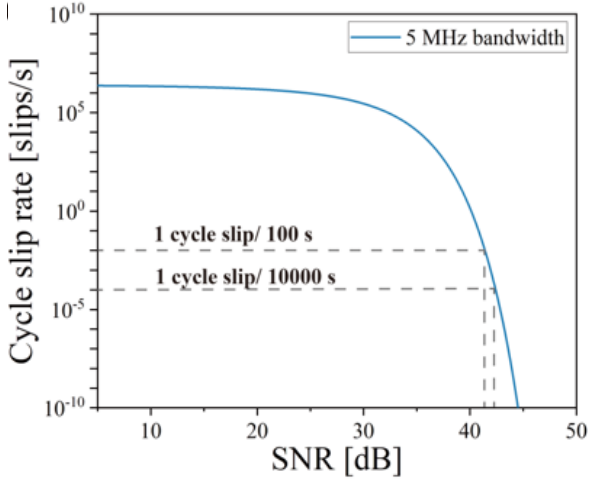


Cycle slips effect on the phase measurement



Effect of cycle slip on the fractional frequency instability

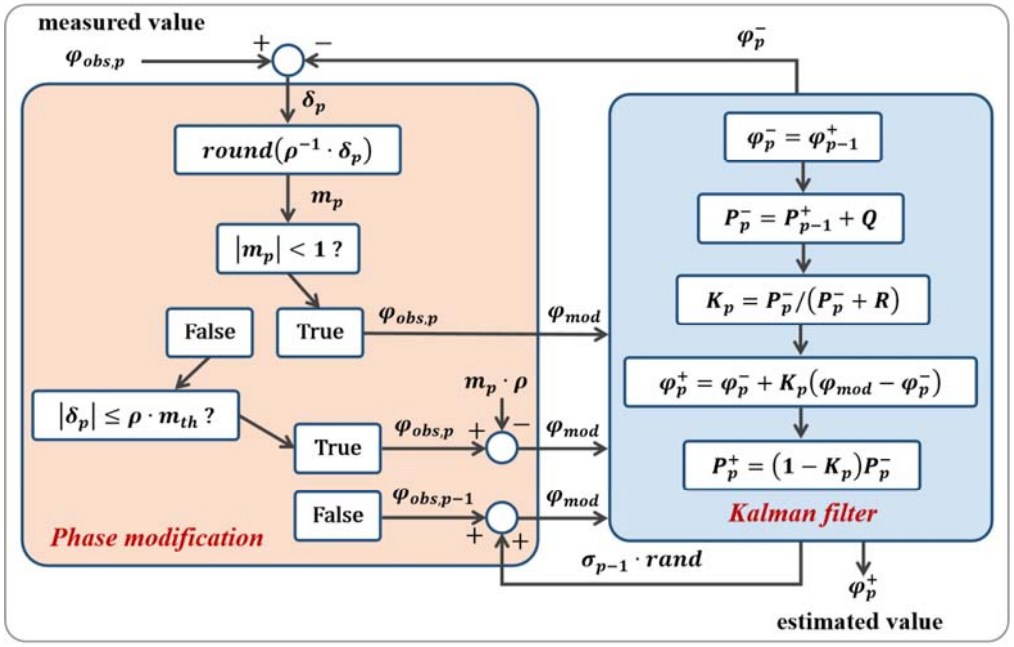




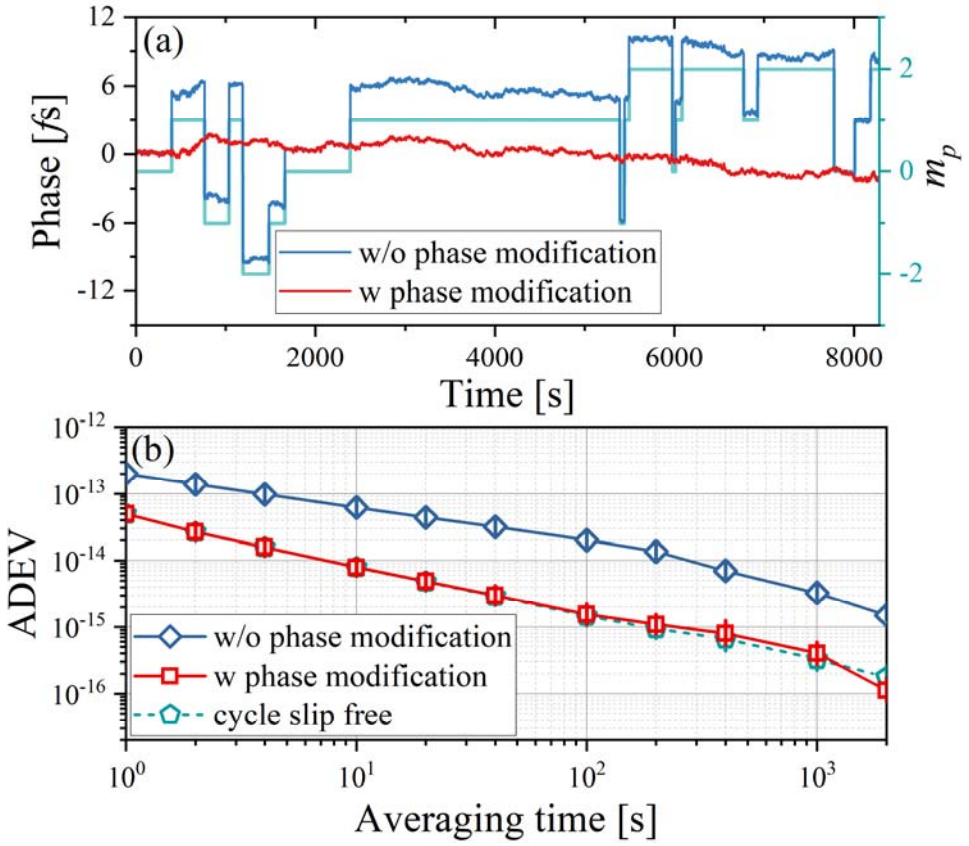
Effect of SNR on phase error/cycle slip

③ Cycle-slip measurement and compensation

- Cycle-clip compensation
  - Kalman filter
  - Neural network



Flow chart of the cycle-slip compensation algorithm based on Kalman filtering

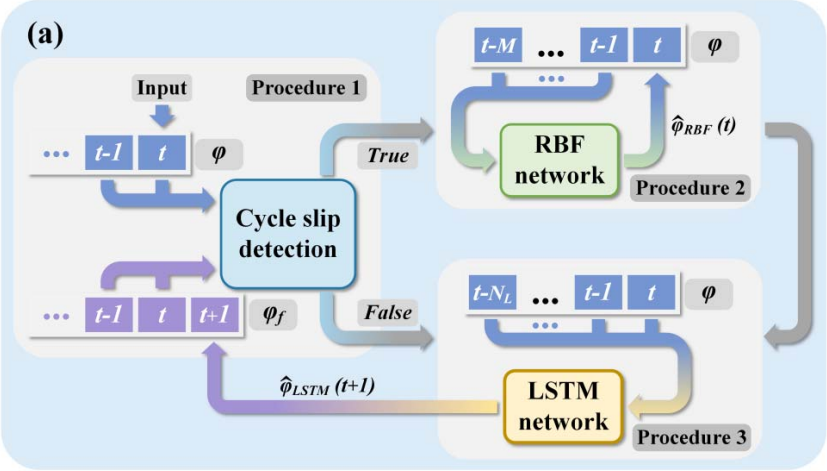


Cycle-clip phase compensation with Kalman filter

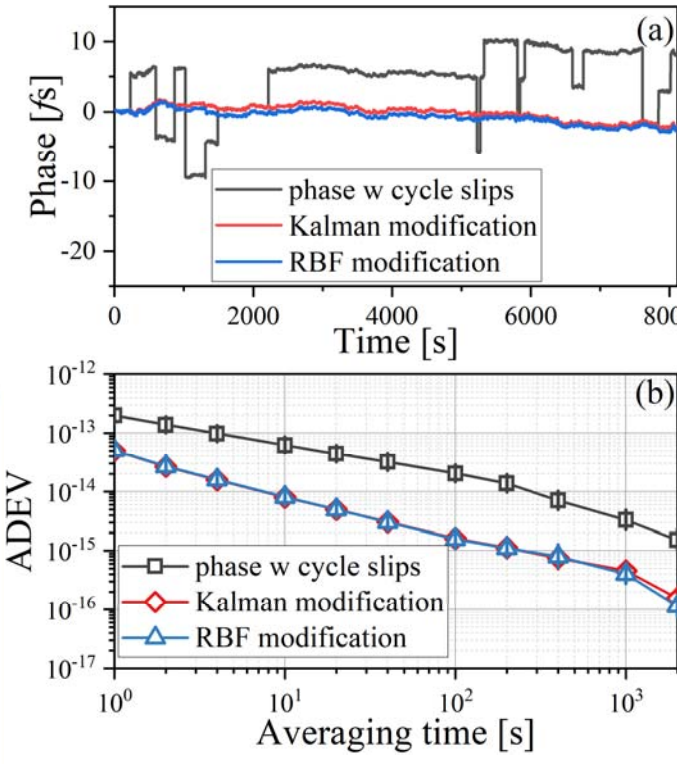
③ Cycle-slip measurement and compensation

❑ Cycle-clip phase compensation with neural network

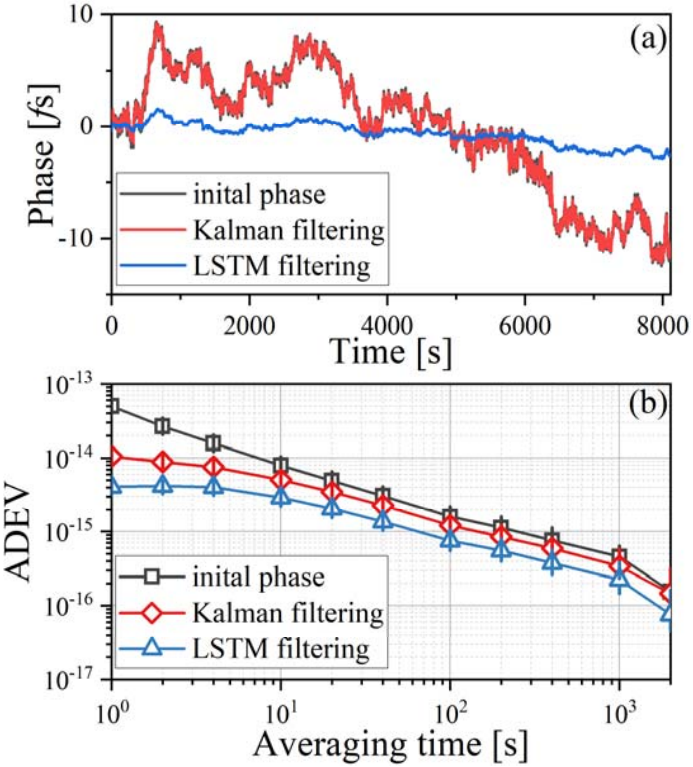
- ◆ Radial Basis Function (RBF)
  - ☺ long-term correlation data
  - ☺ less training set required
- ◆ Long Short Term Memory (LSTM)
  - ☺ high filtering ability
  - ☹ poor long-term predication capability



Flow chart of the cycle-slip compensation algorithm based on neural network



Filtering effect comparison

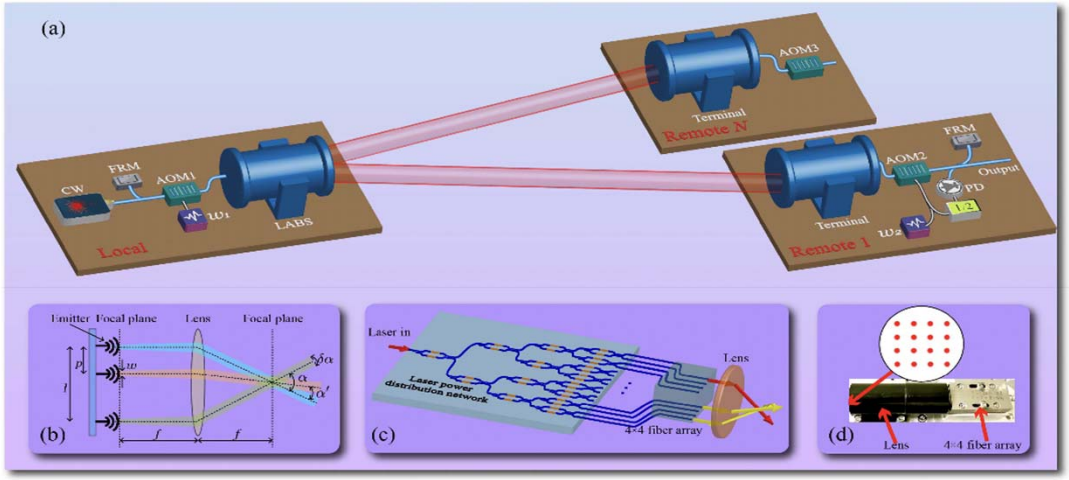


Cycle slip suppression ability comparison

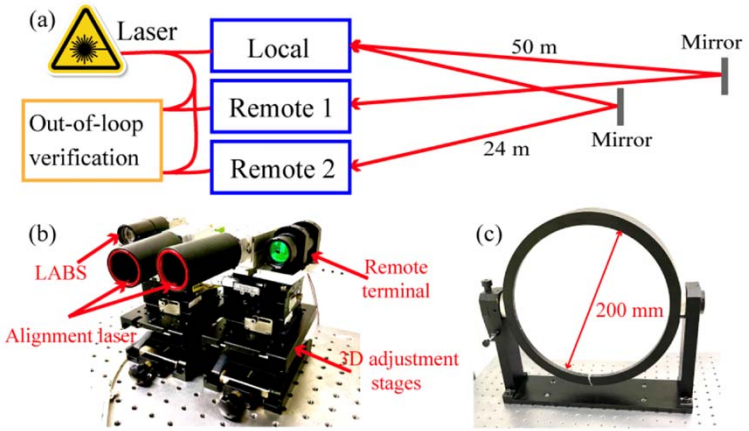
Content

Multiple-node free-space optical frequency transfer

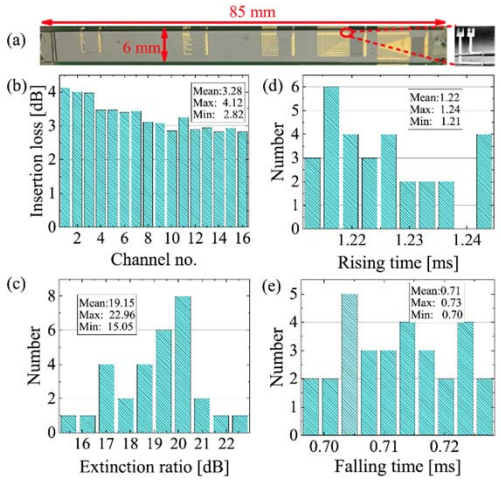
- Chip-based free-space transfer
  - PLC: 1 to 16-channel
  - Passive phase noise compensation
  - 50 m free-space link
  - 4.5×10^{-17}/ 1 s
  - 7.7×10^{-20}/ 20,000 s



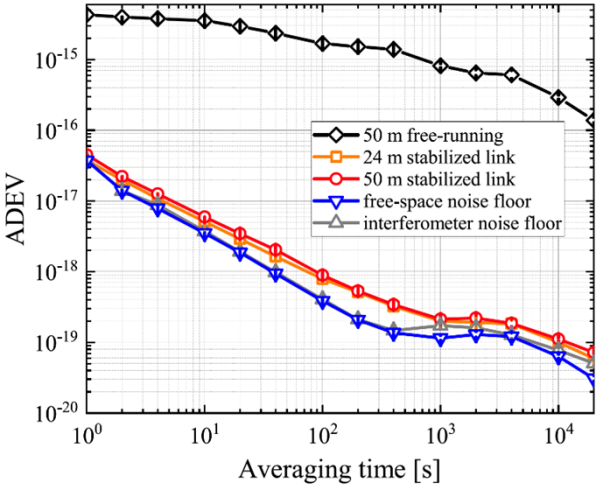
Schematic diagram of the multiple-node system



Experimental setup



PLC circuit characteristic

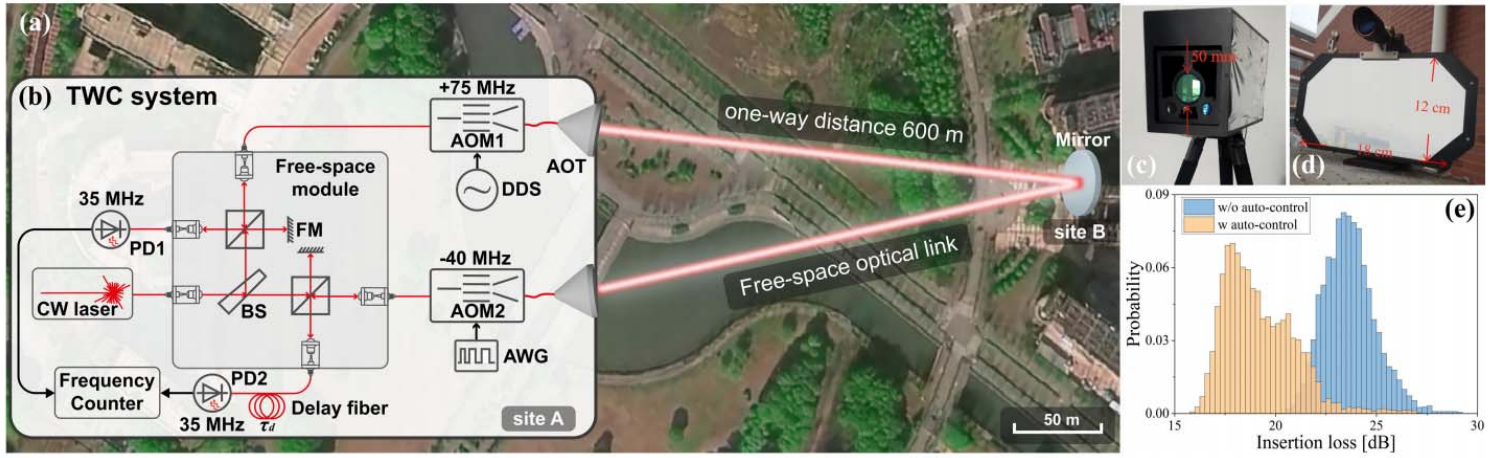


ADEV results

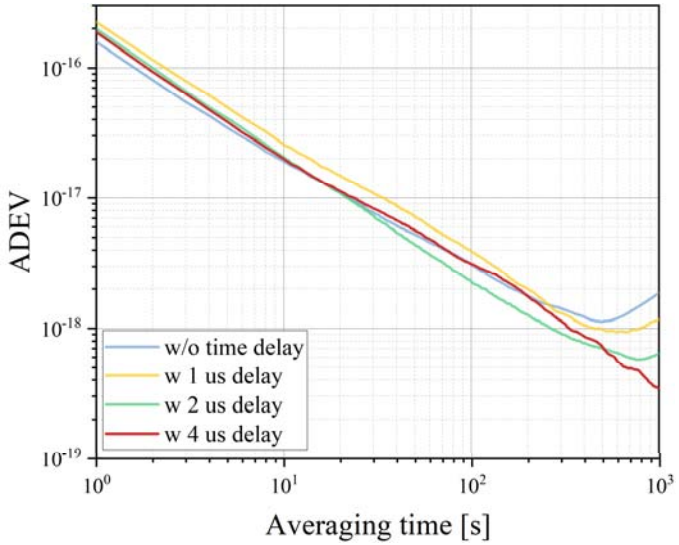
L. Hu, et al., Free-space point-to-multiplepoint optical frequency transfer with lens assisted integrated beam steering, 71, 1-10, 2022

Doppler shift suppressed optical frequency comparison

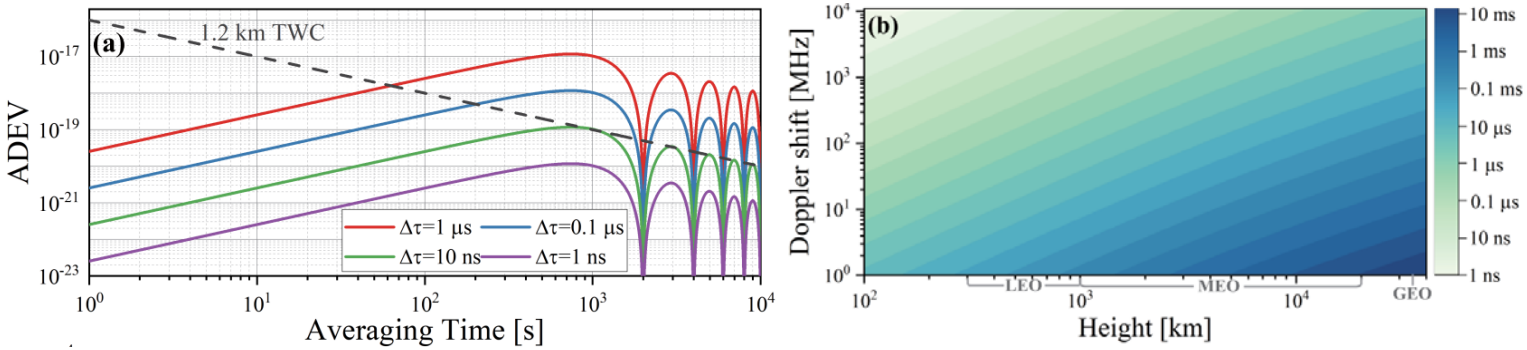
- Free-space optical frequency comparison
  - Time-delay based Doppler effect suppression method
  - 1.2 km free-space link
  - 3.45×10^{-19}/ 1,000 s



Schematic diagram of the multiple-node system



ADEV results



Influence of delay error on Doppler frequency shift compensation

Z. Qiu, et al., Nearly-continuous kilometer-scale free-space optical frequency comparison in the presence of Doppler shift, 73, 1-10, 2024

Field-deployed fiber link measurement

- Part of a high-precision ground-based timing system（NTSC）
- Two parallel fiber links with one fiber length of 1960 km