Cancellation of laser phase noise for high fidelity

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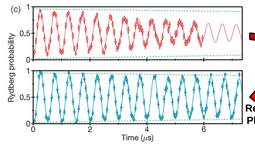
Goal 6
moonshot
大森 PM
大規模・高コヒーレンスな
動的原子アレー型・
誤り耐性量子コンピュータ

What is phase noise ?

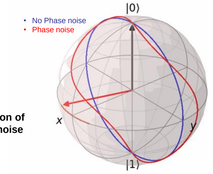
Phase noise decreases fidelity

To improve fidelity and meet the requirement for QEC, 3 main source of errors have been identified : Doppler shift, spontaneous emission, **laser phase noise**.

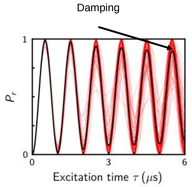
De Léséleuc *et al* 2018 Phys. Rev. A **97**, 053803



Reduction of Phase noise



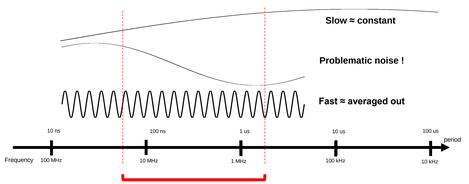
Harry Levine *et al* 2018 Phys. Rev. Lett. **121**



Quantum simulation of spin models with assembled arrays of Rydberg atoms, PhD Thesis S. de Léséleuc

Fourier Frequency and time-scale

Phase noise that matters is in the time-scale of the experiment !

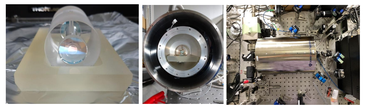


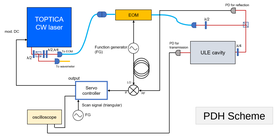
Phase noise measurement

ULE Fabry-Perot cavity, PDH error signal

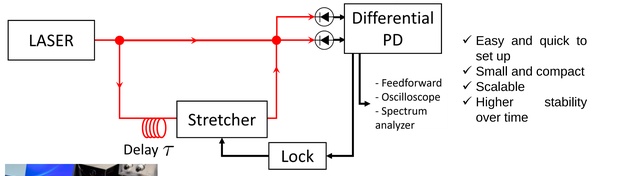
$$s_{\mathrm{FP}}(f) = \frac{K}{1 + 4if/f_c}$$

× Bulky system
× Complex and hard to set up
× Mainly good at low frequencies
× Very sensible to external noise

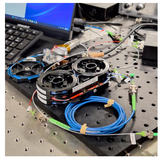


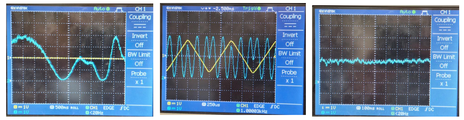


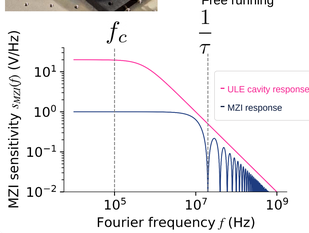
Fiber Mach-Zehnder Interferometer (MZI)



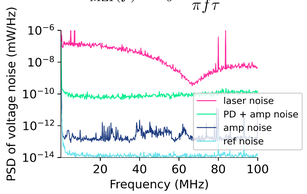
✓ Easy and quick to set up
✓ Small and compact
✓ Scalable
✓ Higher stability over time







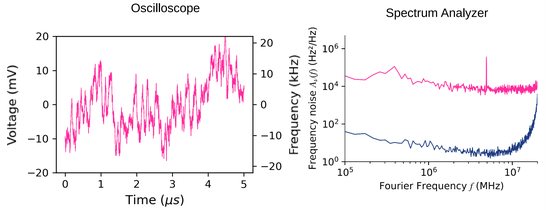
$$s_{\mathrm{MZI}}(f) = s_0 \frac{\sin(\pi f \tau)}{\pi f \tau} e^{-i\pi f \tau}$$



Measurements results

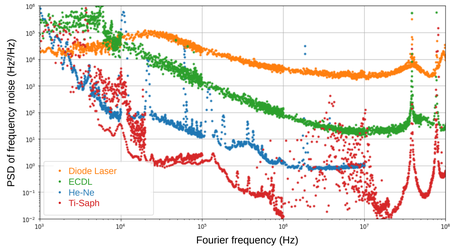
Oscilloscope

Spectrum Analyzer



Remark : The linewidth of the laser is not the relevant quantity to measure

Important information !

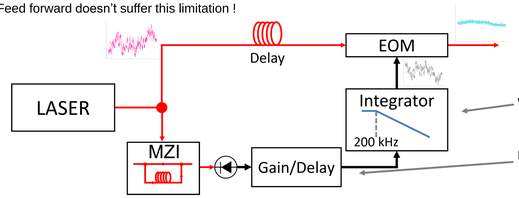


Phase noise cancellation

Feedforward for high frequencies !

Feedback is limited by the time the information takes to go from the measurement point to the correction point. Reaching 1 MHz is already a challenge…

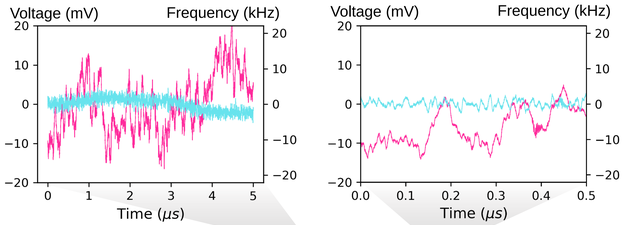
Feed forward doesn't suffer this limitation !

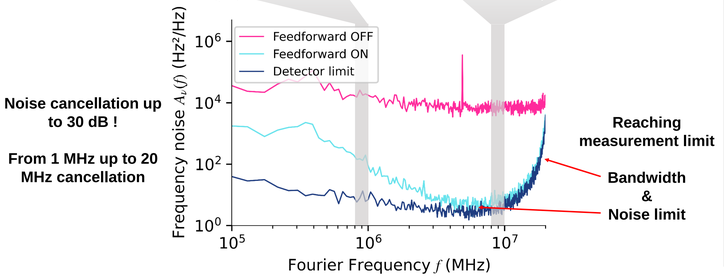


✓ Easy to assemble
✓ Compact and scalable
✓ Good even at high frequencies (> 1 MHz)

Interferometer reads frequency noise
We need to integrate it back to phase noise !

Feedforward requires precise Gain & Delay





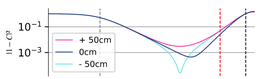
Noise cancellation up to 30 dB !

From 1 MHz up to 20 MHz cancellation

Reaching measurement limit

Bandwidth & Noise limit

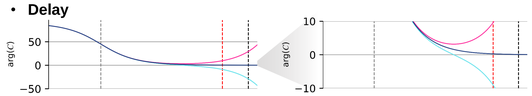
Noise limit



$$C(f) = \pm G \frac{if/f_c}{1 + if/f_c} \frac{\sin(\pi f \tau)}{\pi f \tau} e^{i2\pi f \tau_d}$$

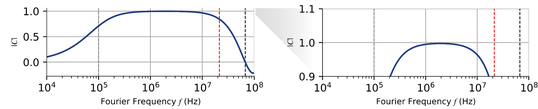
Feedforward requires precise gain & delay

- **Delay**

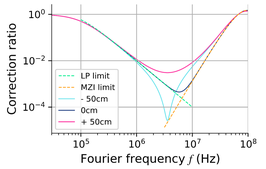


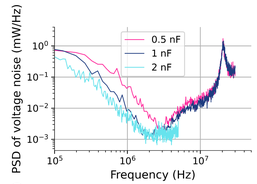
To reach 30dB cancellation, delay must be below 0.5ns = 10 cm

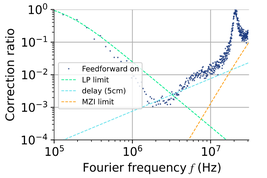
- **Gain**

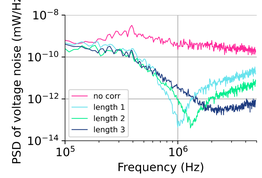


To reach 30dB cancellation, gain must be 0.28dB from unity









Coming soon

Packaging of the phase noise cancellation

Improvement of performances

Electronic passive delay line
Finer gain precision via 0.25dB step attenuator

Rabi oscillation with reduces phase noise

Shine stabilized light on 87Rb atoms and quantify the fidelity improvement gained by feedforward noise cancellation

New system for 960nm doubled to 480nm

Adapt the system to 960nm light and use second harmonic generation to obtain noise cancelled 480nm light used with 780nm in Rydberg excitation

Acknowledgements and references

Thanks

MOONSHOT RESEARCH & DEVELOPMENT PROGRAM

JST 科学技術振興機構
光・量子飛躍フラッグシッププログラム（Q-LEAP）

National Institutes of Natural Sciences
Institute for Molecular Science

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S. de Léséleuc *Quantum simulation of spin models with assembled arrays of Rydberg atoms*, PhD Thesis, Université Paris-Saclay (2018)
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E. D. Black *An introduction to Pound–Drever–Hall laser frequency stabilization* Am. J. Phys. **69**, 79 (2000)
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Li, L., Huie, W., Chen, N., DeMarco, B. and Covey, J.P., *Active cancellation of servo-induced noise on stabilized lasers via feedforward* Phys. Rev. A **18**, 064005 (2022)