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Cesium Laser-Atomic Oscillator

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Laser-atomic oscillator & Push-pull optical pumping

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Push-Pull Laser-Atomic Oscillator

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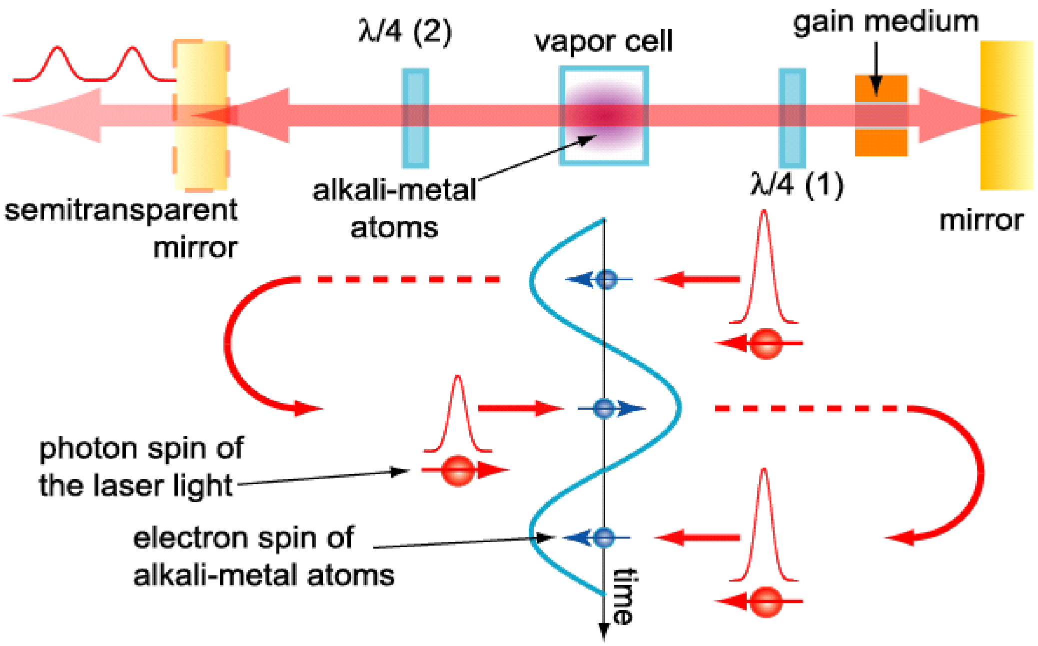
A vapor of alkali-metal atoms in the external cavity of a semiconductor laser, pumped with a time-independent injection current, can cause the laser to self-modulate at the "field-independent 0-0 frequency" of the atoms. Push-pull optical pumping by the modulated light drives most of the atoms into a coherent superposition of the two atomic sublevels with an azimuthal quantum number $m = 0$. The atoms modulate the optical loss of the cavity at the sharply defined 0-0 hyperfine frequency. As in a maser, the system is not driven by an external source of microwaves, but a very stable microwave signal can be recovered from the modulated light or from the modulated voltage drop across the laser diode. Potential applications for this new phenomenon include atomic clocks, the production of long-lived coherent atomic states, and the generation of coherent optical combs.



VOLUME 93, NUMBER 16 PHYSICAL REVIEW LETTERS week ending 15 OCTOBER 2004

Push-Pull Optical Pumping of Pure Superposition States

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A new optical pumping method, "push-pull pumping," can produce very nearly pure, coherent superposition states between the initial and the final sublevels of the important field-independent 0-0 clock resonance of alkali-metal atoms. The key requirement for push-pull pumping is the use of $D1$ resonant light which alternates between left and right circular polarization at the Bohr frequency of the state. The new pumping method works for a wide range of conditions, including atomic beams with almost no collisions, and atoms in buffer gases with pressures of many atmospheres.

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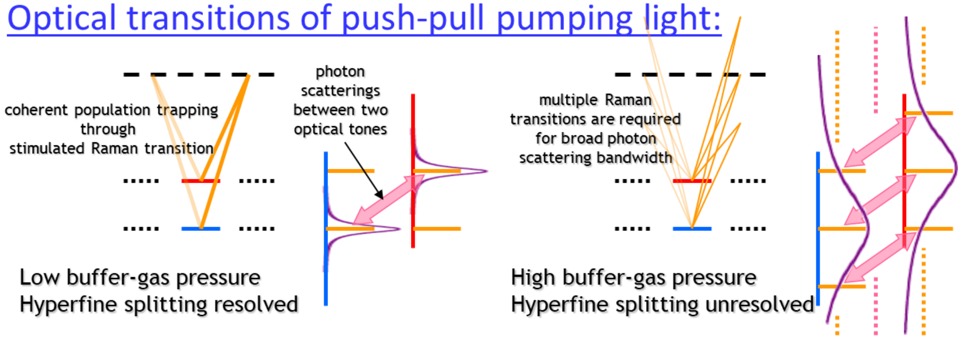
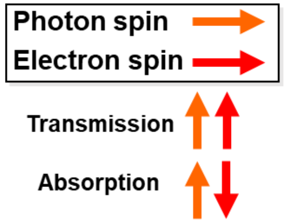
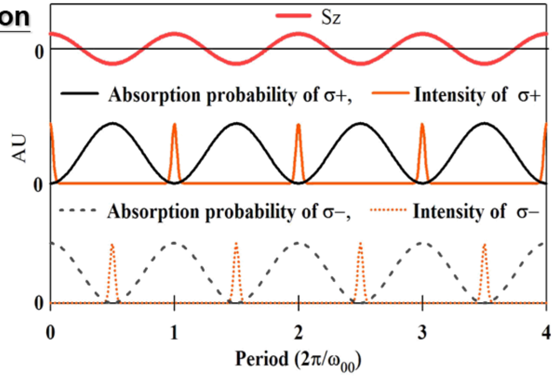
Optical transitions of push-pull pumping light:



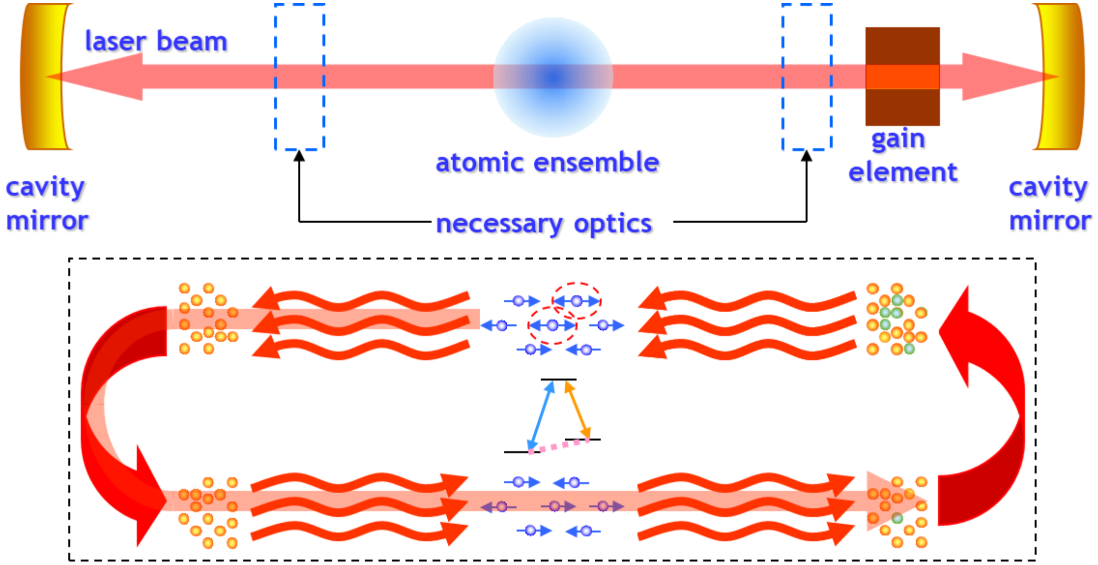
Photon absorption cross section

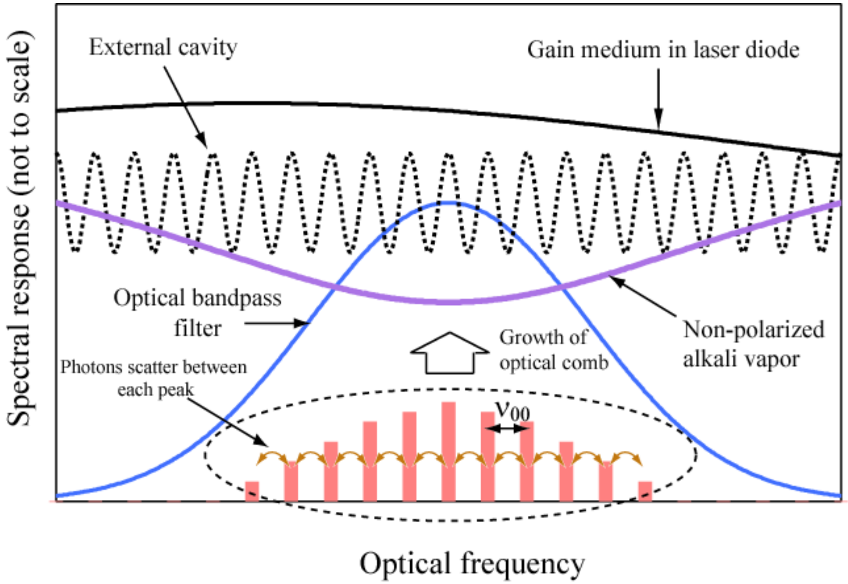
$$\sigma_{D1} = \sigma_0(1 - 2\mathbf{s} \cdot \langle \mathbf{S} \rangle)$$

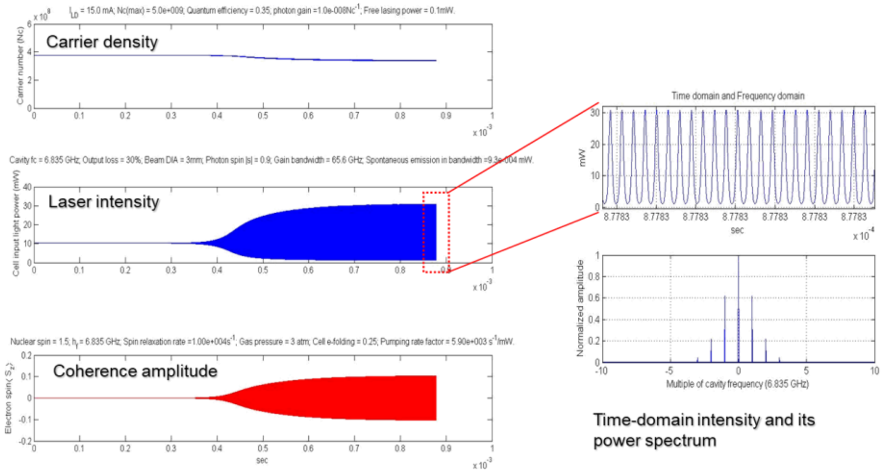




Laser-atomic oscillator in frequency domain







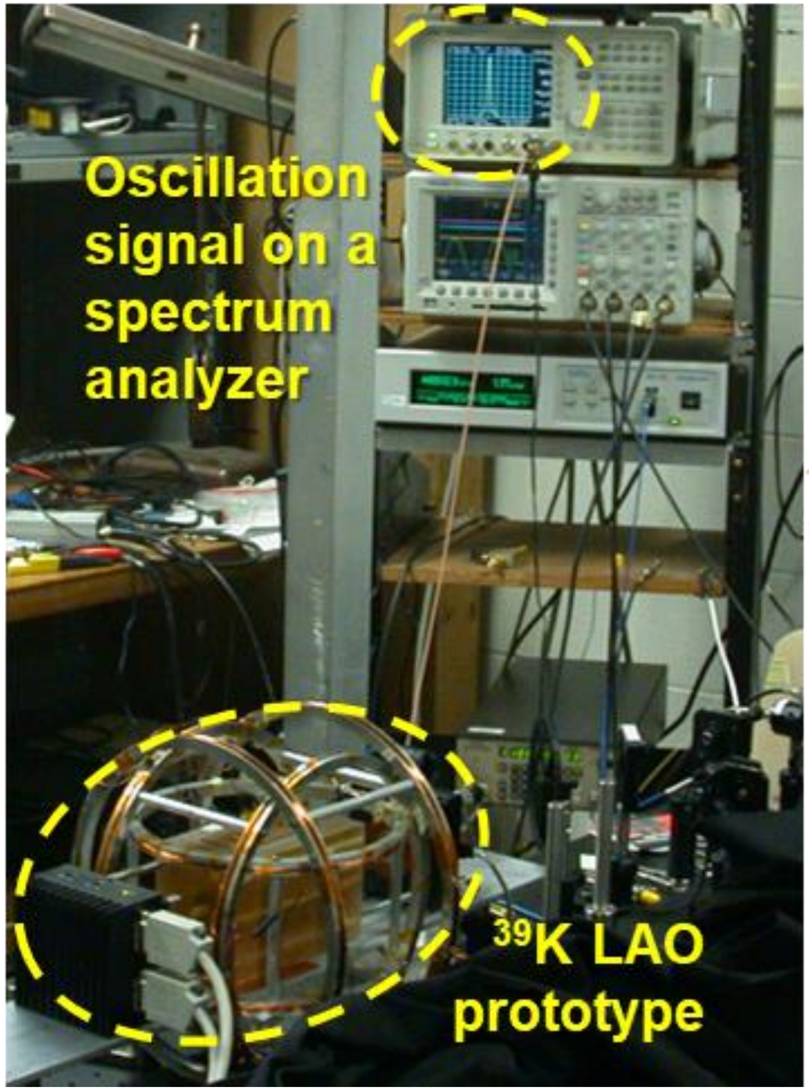
Quantum picture:

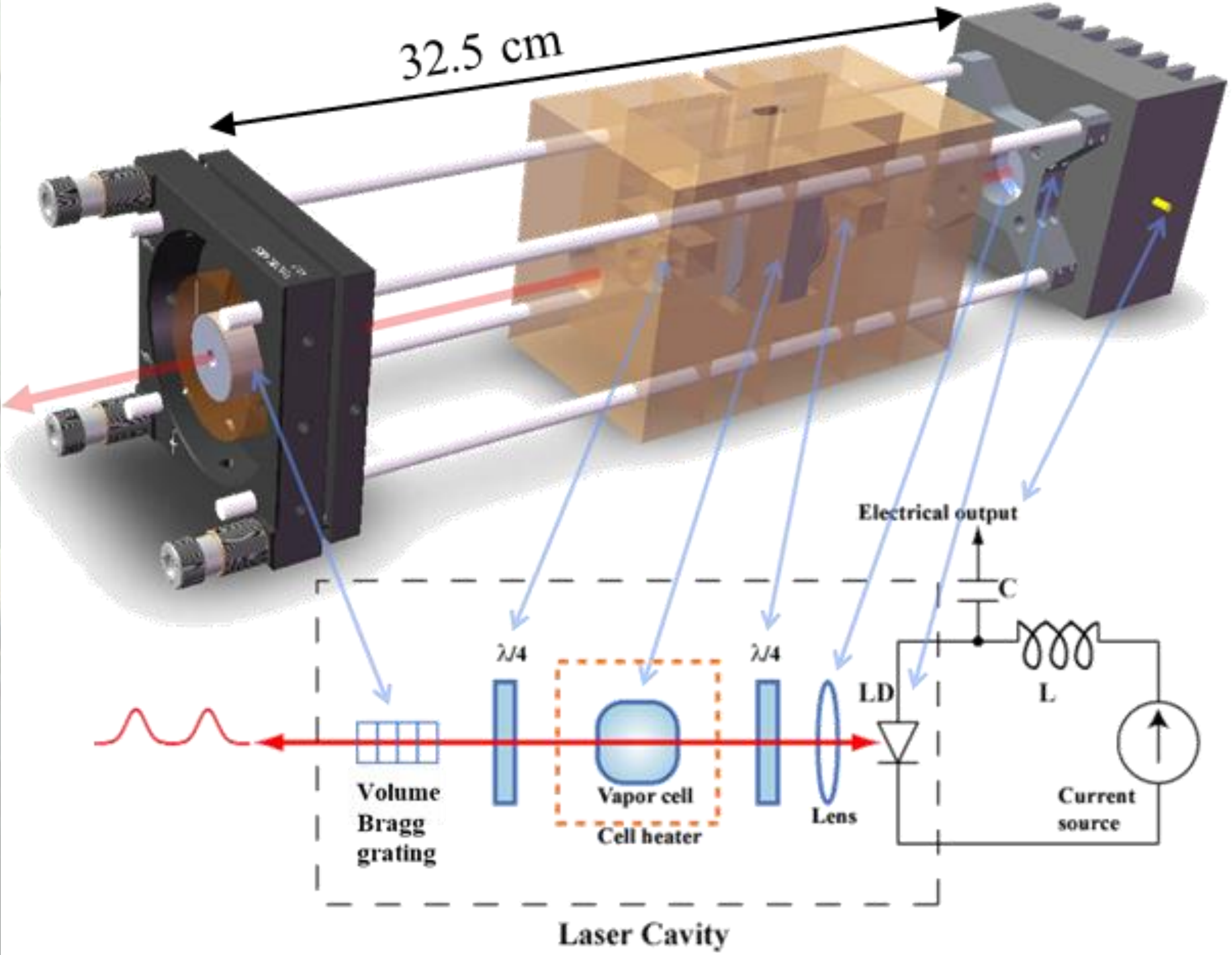
Photon pairs → atomic coherence → photon pairs → amplified by gain element → cycling.

Semi-classical picture:

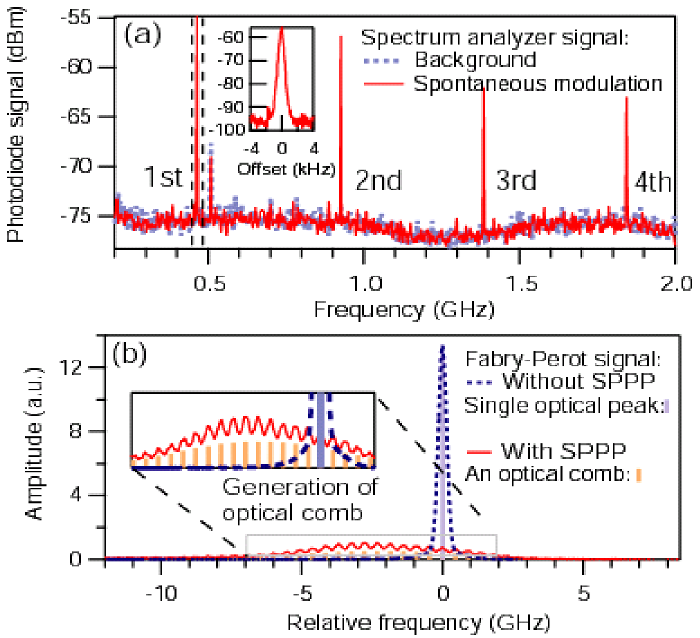
Photon spin (circular polarization) modulation → atomic spin oscillation → photon spin (circular polarization) modulation → amplified by gain element → cycling.

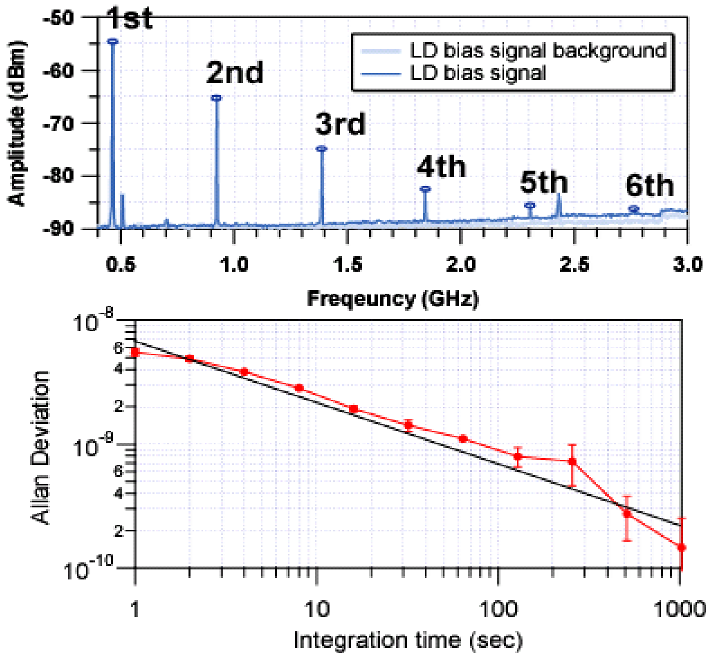
Priorly demonstrated ^{39}K laser-atomic oscillator (LAO)

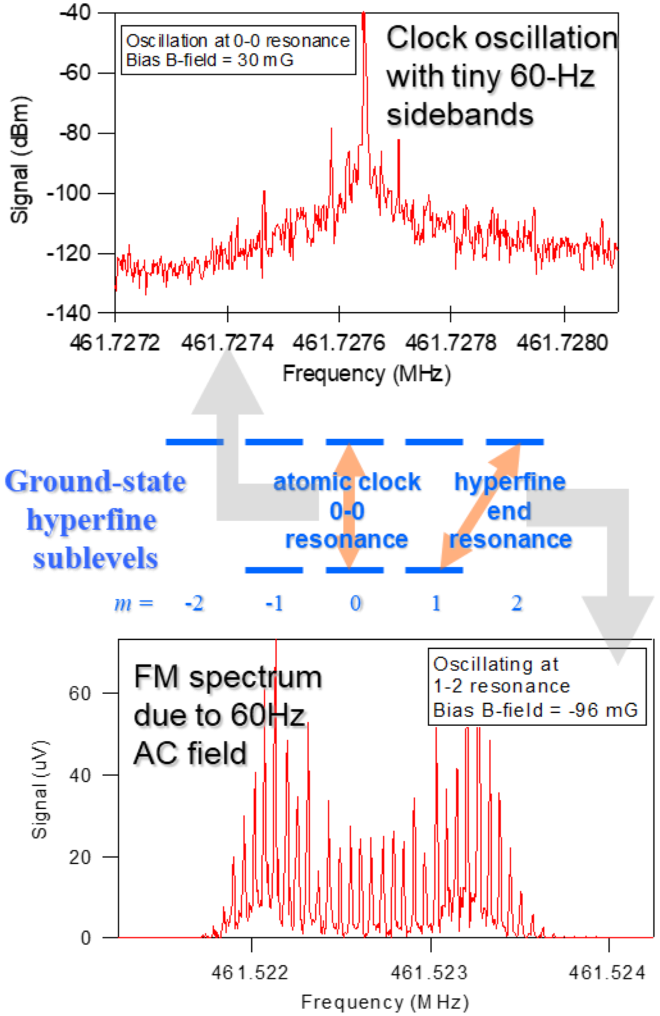


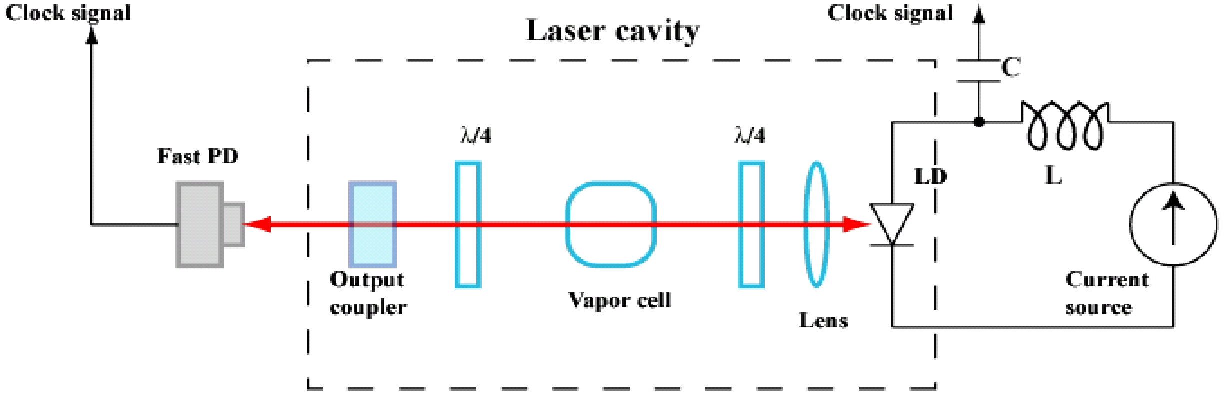


Oscillation signals of the ^{39}K-LAO









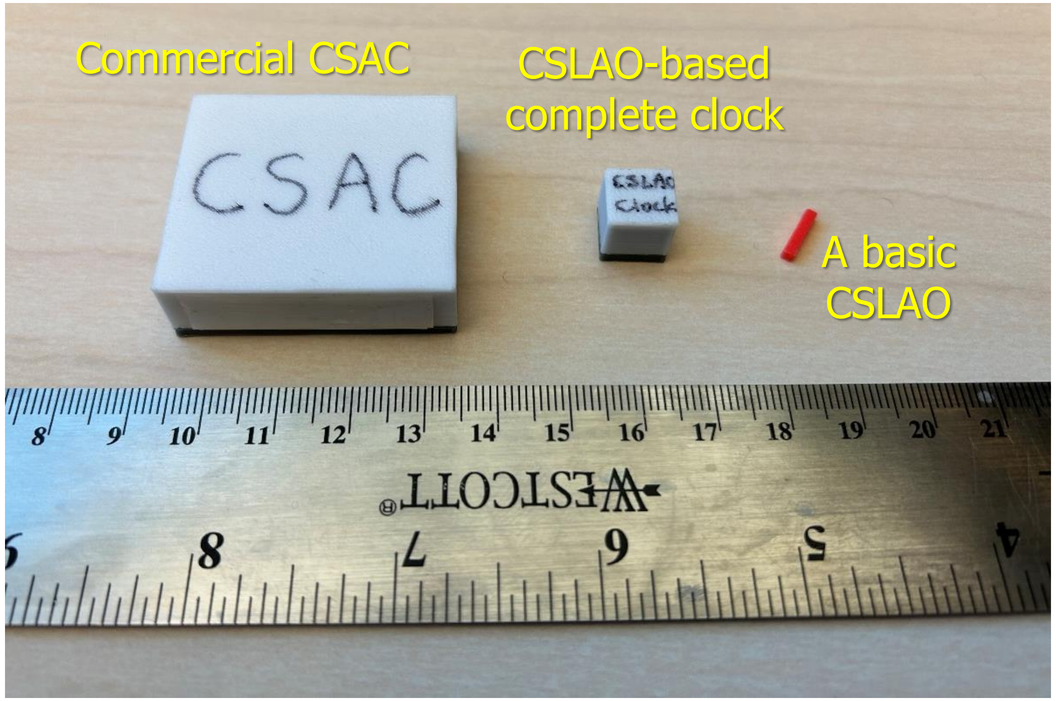
An LAO can also be an earth-field, high-sensitivity (e.g., ~50 fT/Hz$^{1/2}$ from -100 dBc/Hz phase noise), and high dynamic range atomic magnetometer.

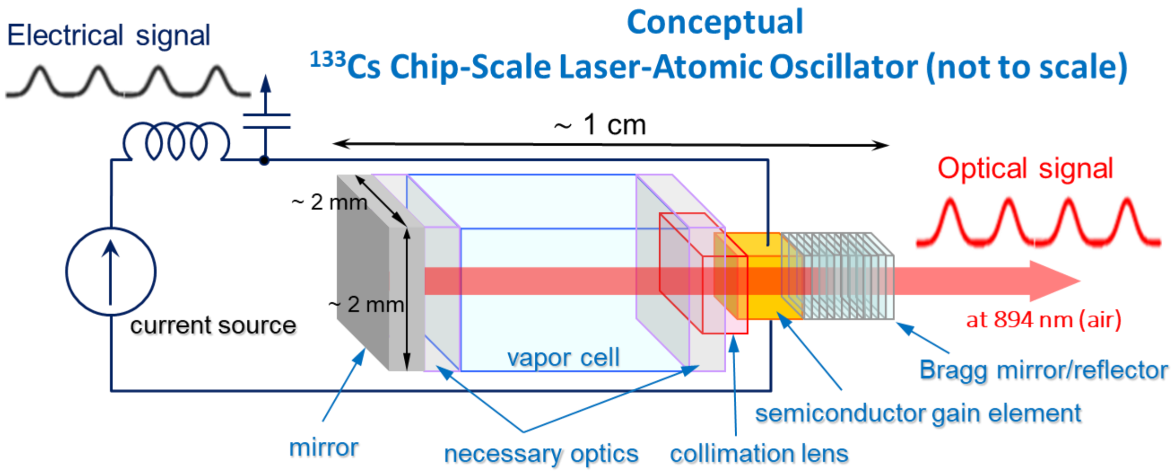
Why cesium laser-atomic oscillator?

- Since the first, highly miniaturized atomic clock "Chip-Scale Atomic Clock (CSAC)" was commercialized in 2011, **the desire of pursuing low size, weight, and power (SWaP) atomic-clock devices continues**.
- **CSAC is a passive atomic clock**, and the complexity of its peripheral electronics leads to a volume ≥ 15 cm^3, about the **size of a matchbox, not truly "chip-scale."**
- **An LAO is an active atomic clock, and its simplicity eliminates major SWaP burdens**, e.g. a local oscillator, a microwave synthesizer, the clock-loop control electronics, and a possible atoms/ions trapping mechanism in a general passive atomic clock.
- For an LAO device, only one of the device dimensions has to match the microwave transition wavelength, and therefore, it greatly reduces the device volume.
- By changing atomic species from ^{39}K to ^{133}Cs for making an LAO, **the large cesium hyperfine frequency at 9.2 GHz can in-principle leads to a ^{133}Cs-LAO with a very small size (≤ 0.1 cm^3), a true chip-scale atomic clock.**

Advantages of cesium laser-atomic oscillator

❖ We aim to develop Chip-Scale Laser-Atomic Oscillator (CSLAO), based on cesium (Cs) atoms, which naturally has 20x shorter wavelength compared to a ^{39}K-LAO.

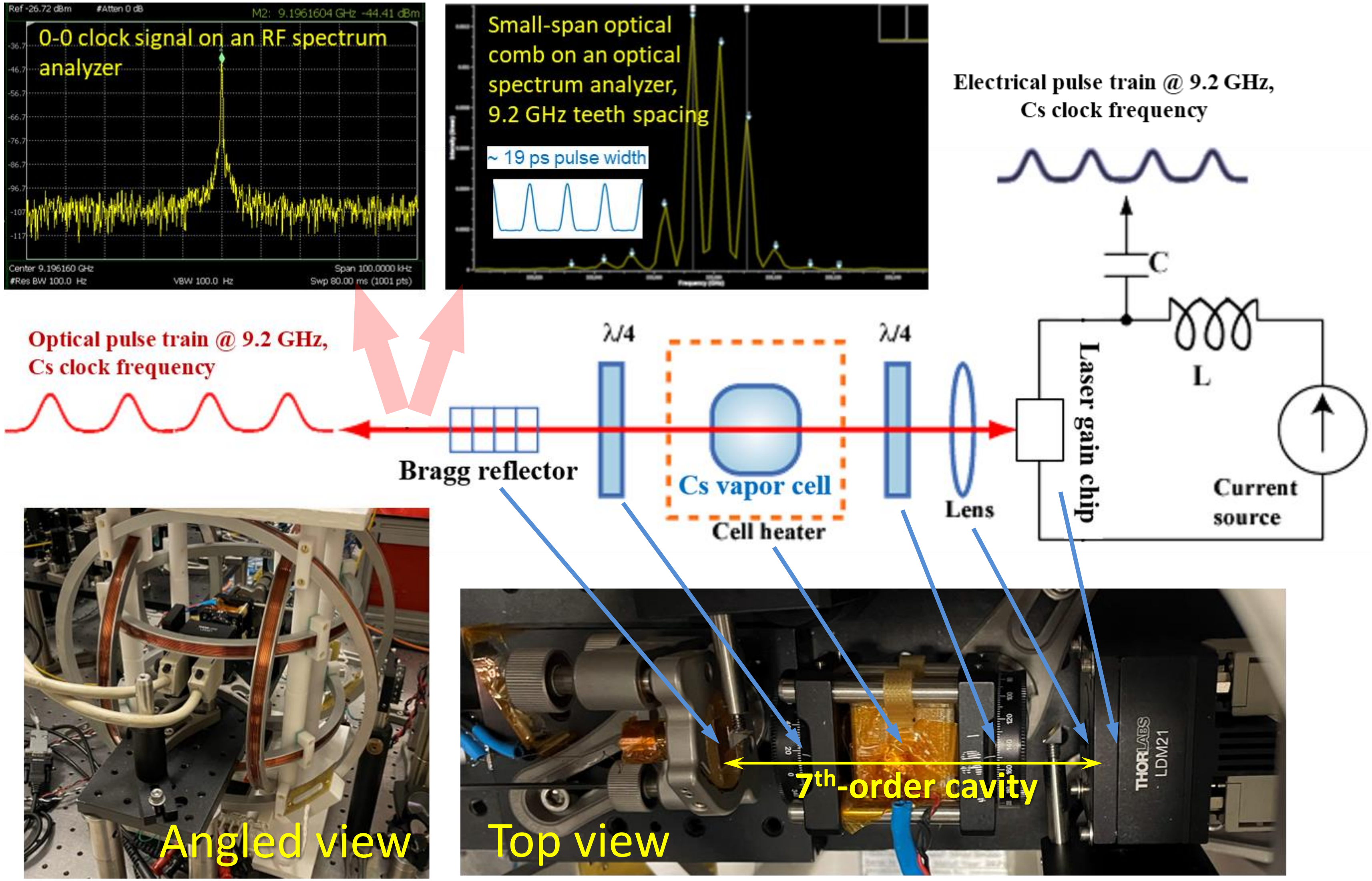




Anticipated features of a basic-version CSLAO:

- Low-power (≲20 mW, estimated based on the prior studies)
- Extremely small (≪1 cm^3)
- Low-g-sensitivity ($10^{-12} \sim 10^{-14}$/g, calculated based on the prior studies)
- Delivering stable electrical and optical timing signals
- Intrinsic frequency stability: 20x better in short term and up to 400x better in long term compared to ^{39}K-LAO if there are no other dominant frequency-drift mechanisms.

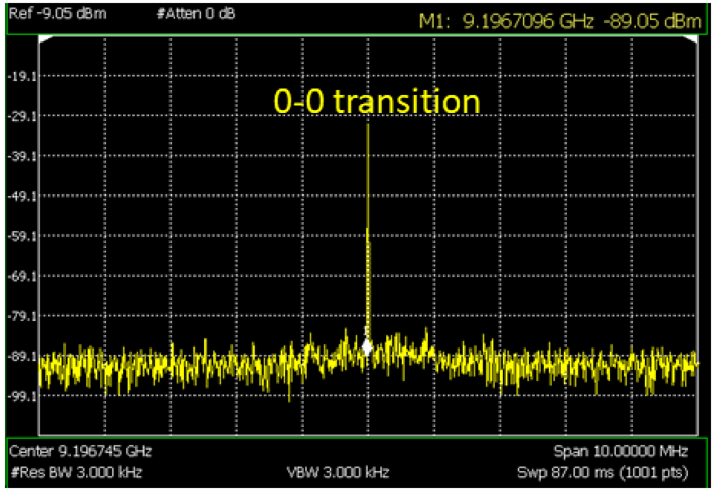
First Cs-LAO demonstrated in history!

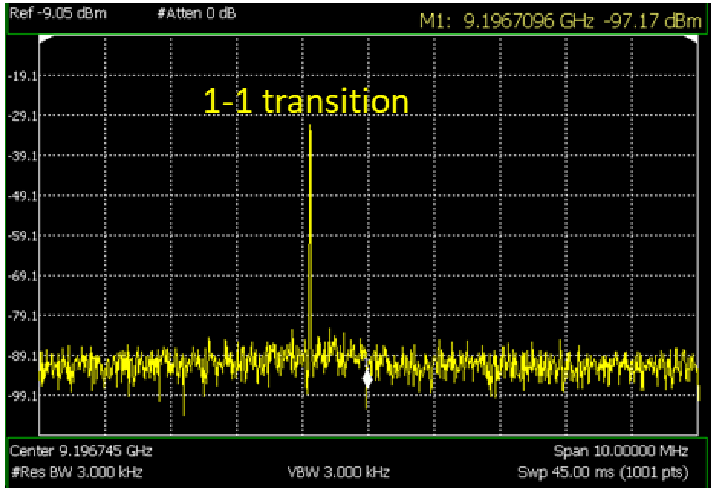


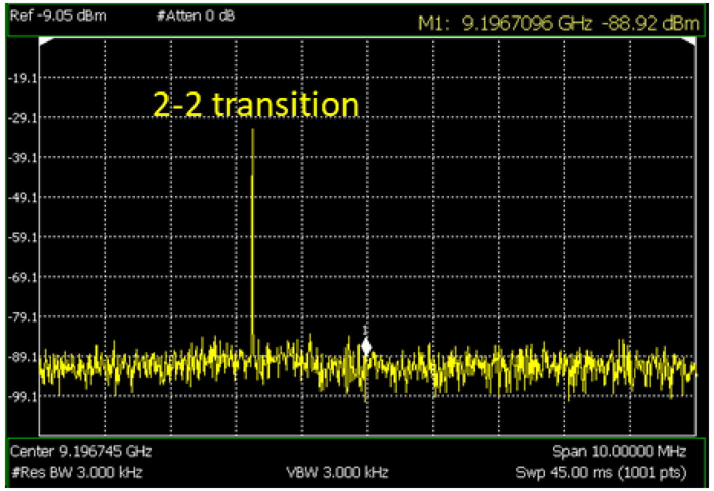
- **The benchtop Cs-LAO setup is designed for adjustability and flexibility, and thus, it has poor mechanical stability.**
- The short-term stability is $< 10^{-9}$ limited by the cavity instability.
- The cavity instability will be mitigated once we build a compact CSLAO assembly.
- **Currently, the oscillation signal is detected optically** using an ultrafast PD. But we shall observe the electric signal once the electric coupling is made.

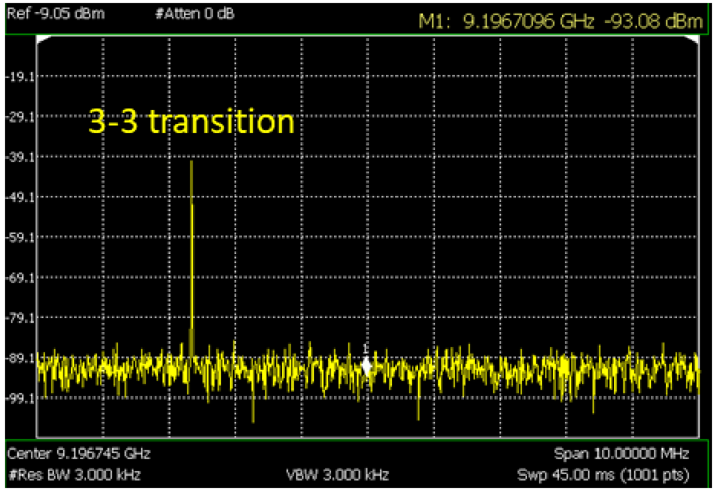
Cs-LAO oscillates at different transitions

By adjusting the cavity settings, we can make a Cs-LAO oscillate at different Cs hyperfine transitions. **Therefore, this Cs laser-atomic oscillator can be used as a clock or a magnetometer.**

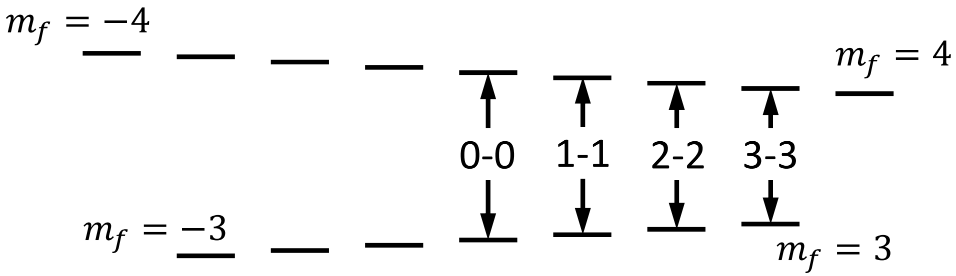


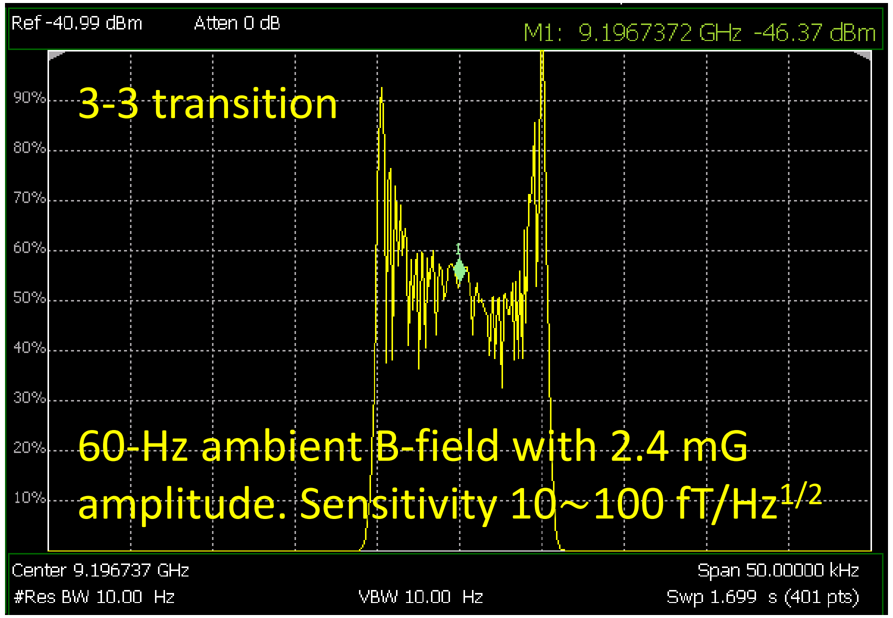






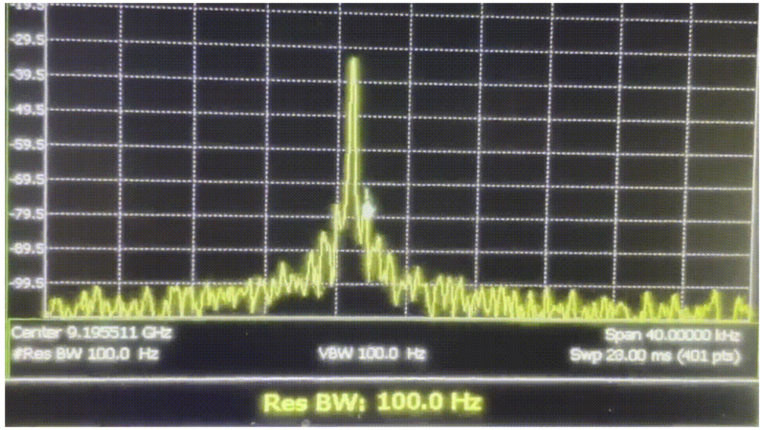
Cs ground-state hyperfine sublevels



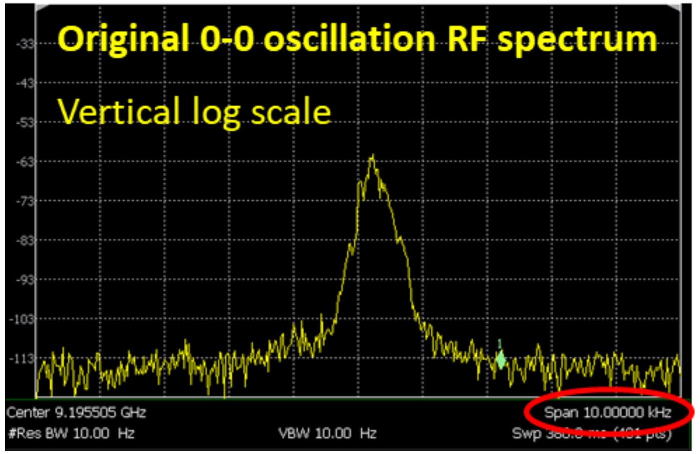


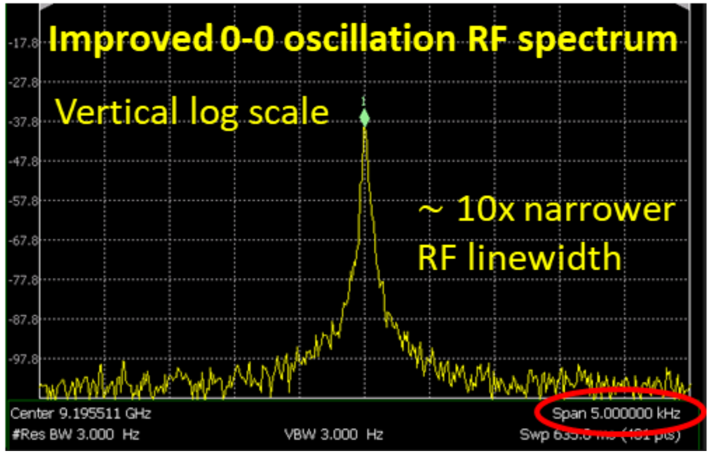
Improvement of frequency drift and phase noise

Improving the frequency drift of the oscillation signal by enhancing mechanical stability:



Reducing the phase noise of the oscillation signal by optimizing operating parameters:

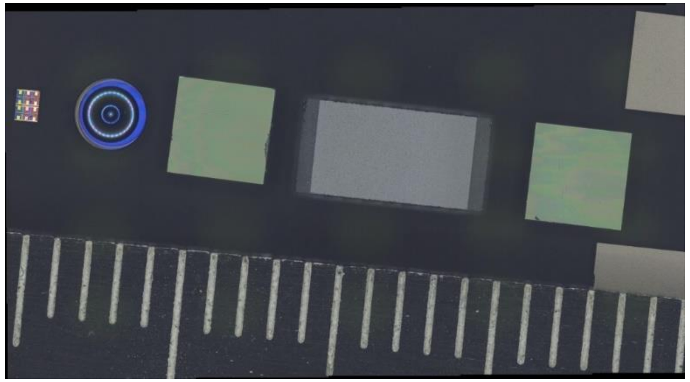




Outlook

- **Laser-atomic oscillator (LAO) is unconventional active atomic oscillator, and CSLAO is unique, unprecedented, and highly miniaturized atomic-device technology.**
- **The simplicity of CSLAO enables very-low SWaP, vapor-cell-based atomic clocks and magnetometers.**
- **Developing CSLAO is challenging but high-payoff. Success of this technology development will enable true chip-scale atomic clock devices.**

CSLAO Components in Tray



CSLAO Components