C11-1: A CMOS Molecular Clock Probing 231.061-GHz Rotational Line of OCS with Sub-ppb Long-Term Stability and 66-mW DC Power

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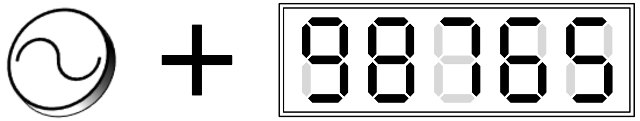
Outline

- **Motivations**
- Rotational Spectrum of OCS Molecules
- Fundamentals of Timekeeping
  - Wavelength Modulation Spectroscopy
  - Clock Feedback Loop
  - Lab-Scale Molecular Clock
- The First Molecular Clock on CMOS
  - Architecture
  - CMOS TX/RX chipset
  - Measurement Results
- Conclusion

What is a clock and how to characterize it?

- Clock = oscillator + counter

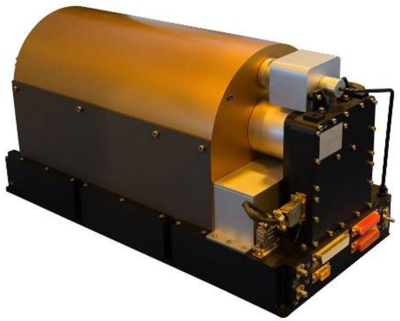


= Readout

Oscillator   Counter

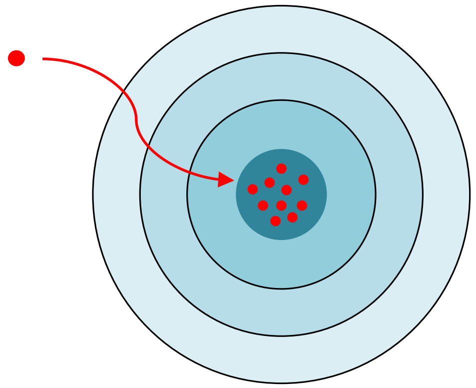
Pendulum clock

Crystal oscillator

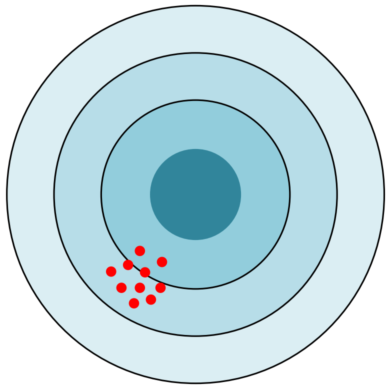


Atomic clock

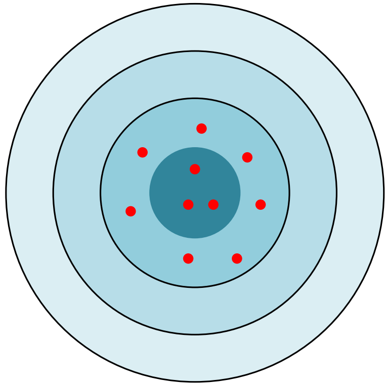
- Stability and accuracy



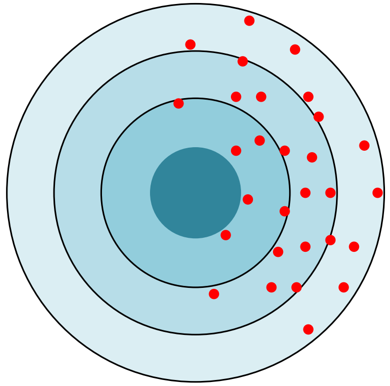
Stable and accurate



Stable, inaccurate



Unstable, accurate



Unstable, inaccurate

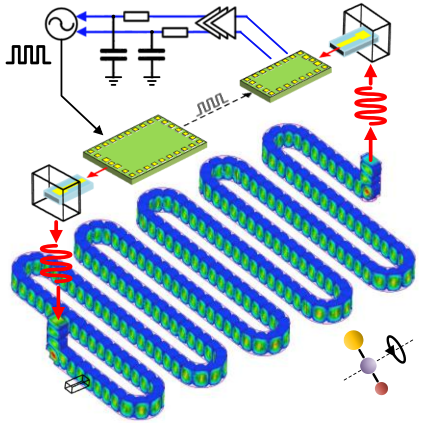
[1] Robert Lutwak, Principles of Atomic Clocks, 2011.

Why do we need a new, portable clock?

- Applications: wireless comm., sensor networks, instruments, engineering

Oven controlled crystal oscillator (OCXO), Crystek CO27VH15DE

Chip scale atomic clock (CSAC), Microsemi SA.45s



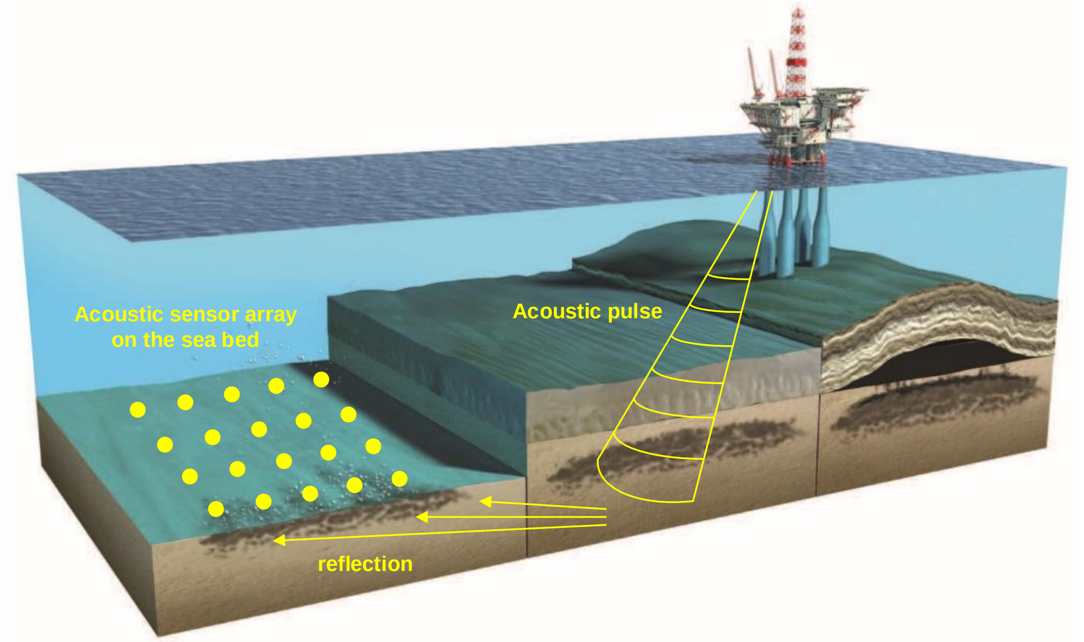
CMOS molecular clock
(This work)

	Stability (σ_y,$\tau=10^3$s)	Volume	Start-up	Power	Cost
OCXO, CO27	~10^{-8}	18cm^3	3min	1.7W	~$100
CSAC, SA.45s	10^{-11}	16cm^3	<3min	120mW	~$1,500
Molecular Clock*	10^{-11}	<10cm^3	<1s	<100mW	<$10

*Predicted based on the current experiment results.

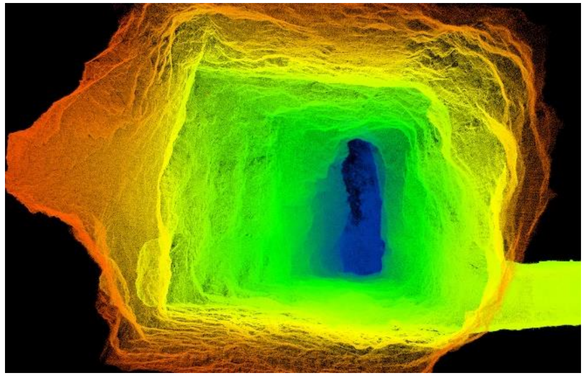
Perspective: Array Imaging, Navigation and Data Link w/o GPS

- Improve the data coherency of multiple sensors.
- Improve the navigation accuracy and synchronization of data link.



Reflection seismology for oil exploration on the sea bed with large acoustic sensor array

[2] www.microsemi.com



Drones for tunnel inspection

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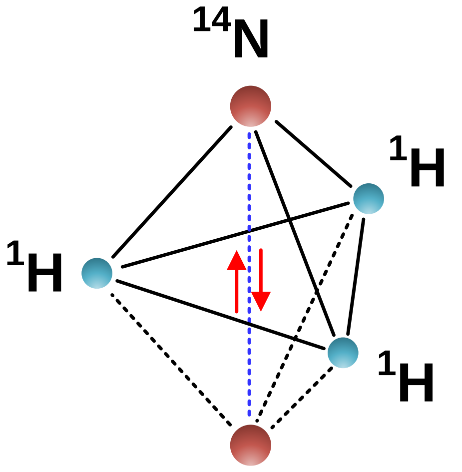
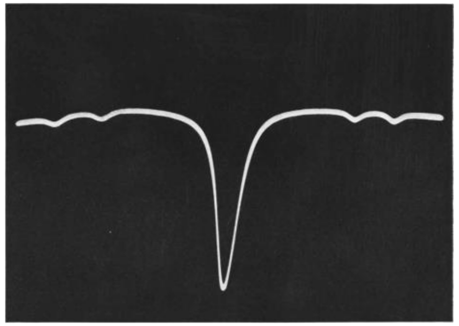
The First Molecular Clock using Inversion Spectrum of NH_3

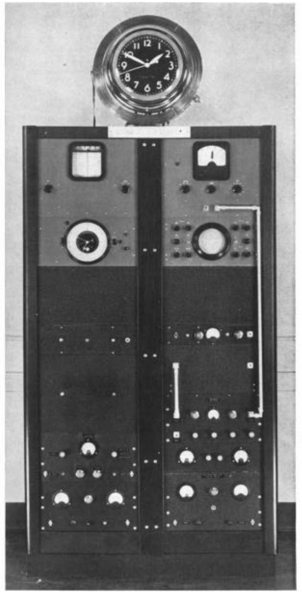
- Ammonia (NH_3) inversion by tunneling of ^{14}N atom through plane of ^{1}H atoms.

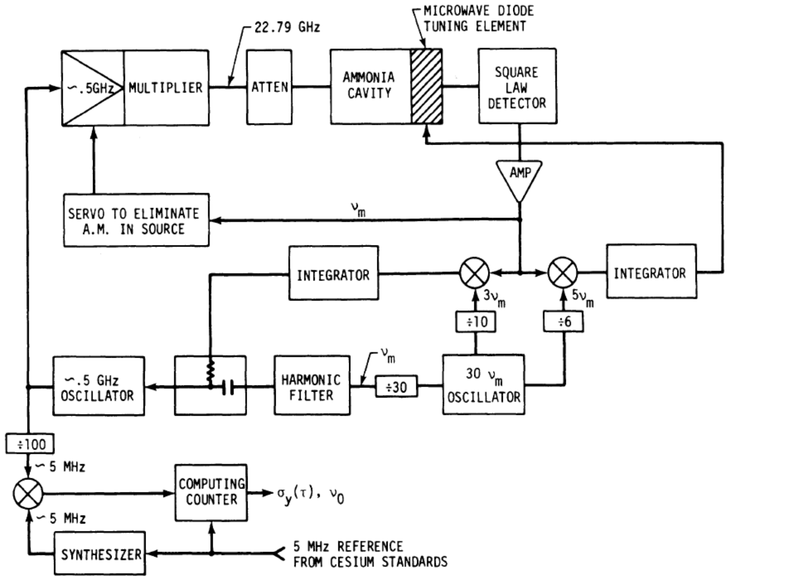




Inversion spectral line of NH_3 at 23.87GHz

- Advantages:
  - All electronics
  - Simple clock configuration
- Disadvantages:
  - Weak absorption intensity
  - Bulky gas cell due to the long wavelength



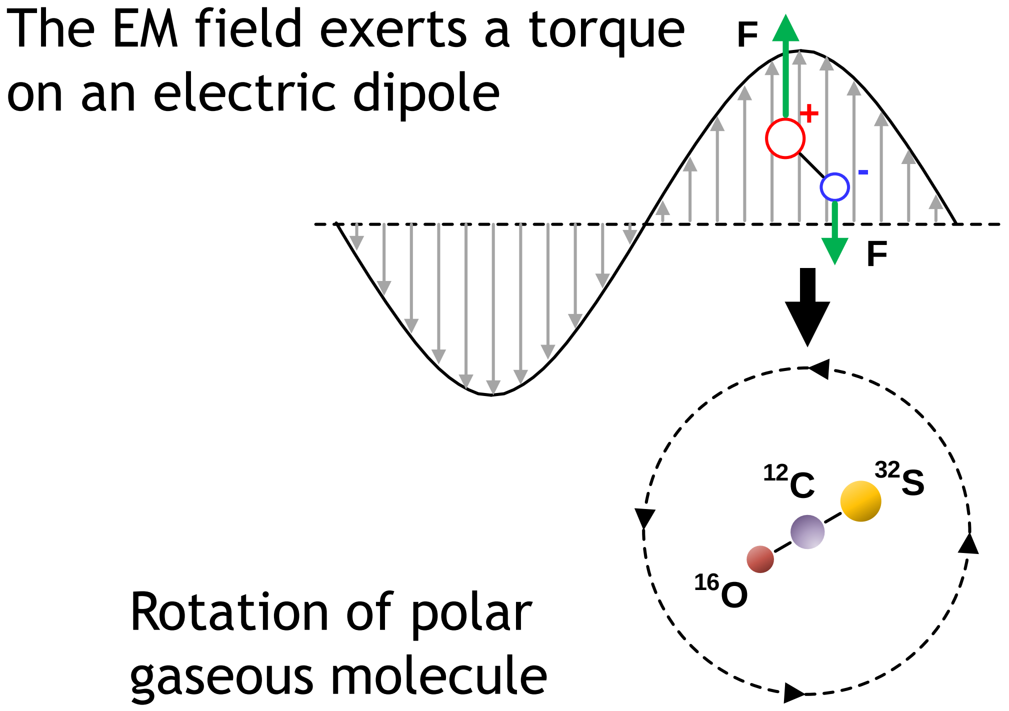


Early Ammonia clock [4] Wineland's Ammonia clock [5]

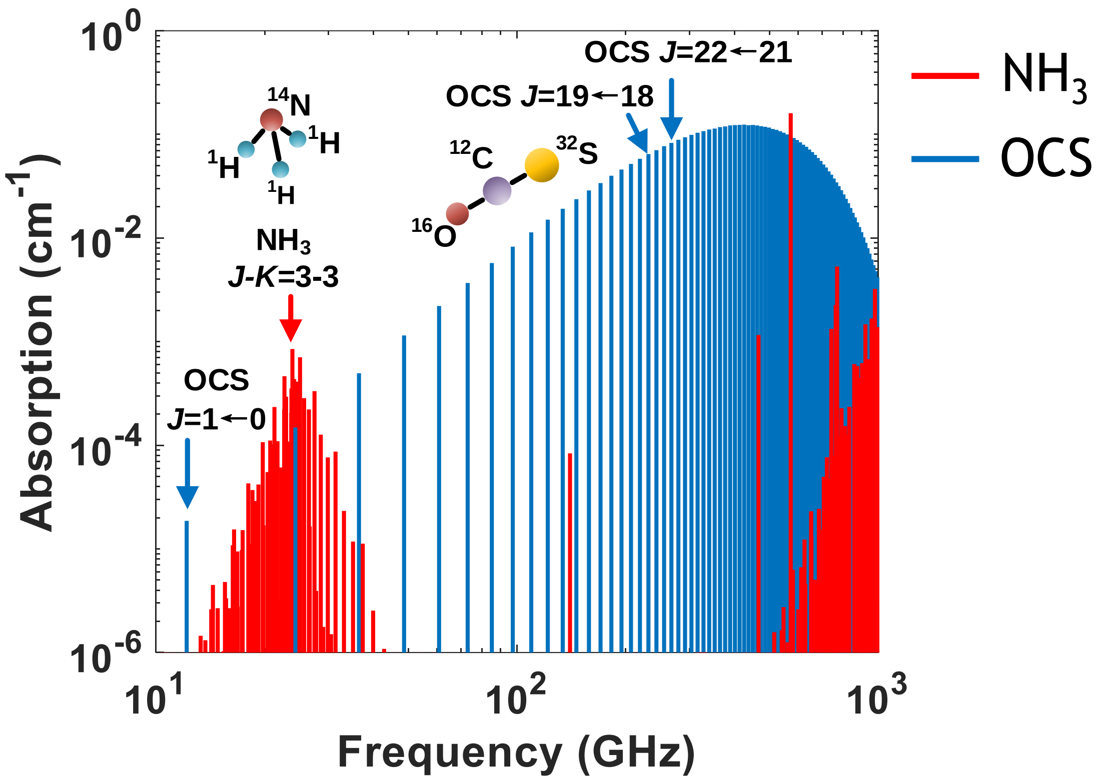
[3] C. H. Townes, J. Appl. Phys. 22, 1365–1372 (1951).
[4] H. Lyons, Scientific American, Vol. 196, No. 2, pp. 71-85, Feb. 1957.
[5] D. J. Wineland, et.al, IEEE Trans. on Instru. and Meas., vol. 28, no. 2, pp. 122-132, June 1979.

Rotational Spectrum of Carbonyl Sulfide (OCS)

- Stronger absorption intensity (100×) and higher quality factor (2×) than NH_3.
- Sub-THz band → 0.1× wavelength → compact gas cell.



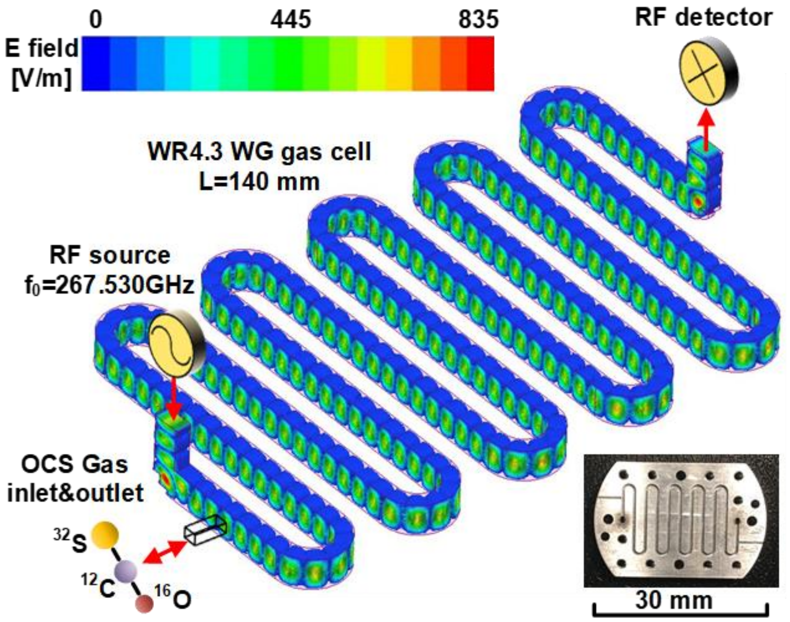
[6] hyperphysics.phy-astr.gsu.edu



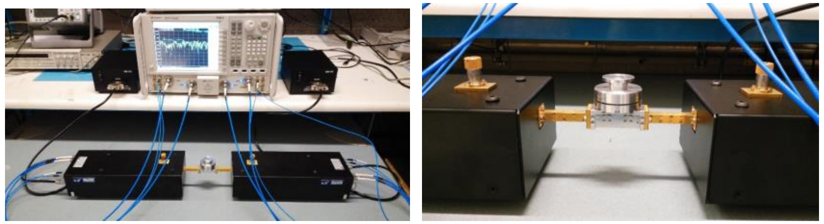
Simulated spectrum

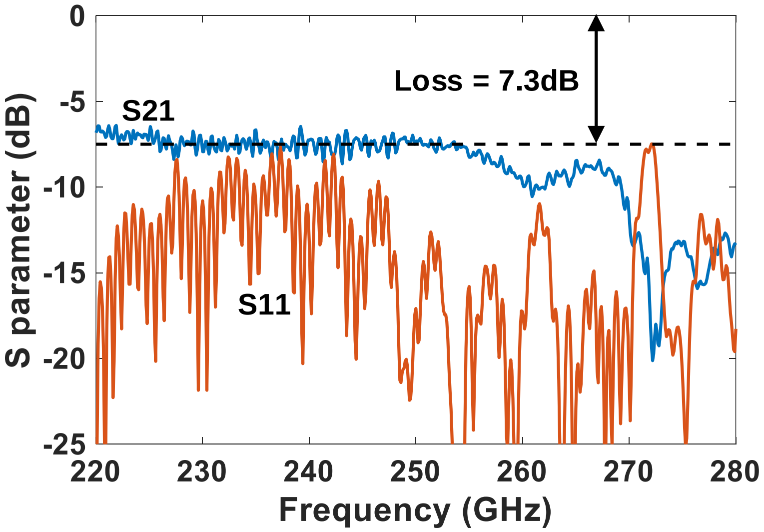
A Compact WR4.3 Waveguide Gas Cell

- Gas cell volume is reduced from 1~2 liter (NH_3 [5]) to 83 mm^3 (OCS).
- Designed with optimum length, total loss (including sealing) is 7.3 dB.



WR4.3 waveguide gas cell
Cross section= 1.092×0.546 mm^2
Total length=140 mm





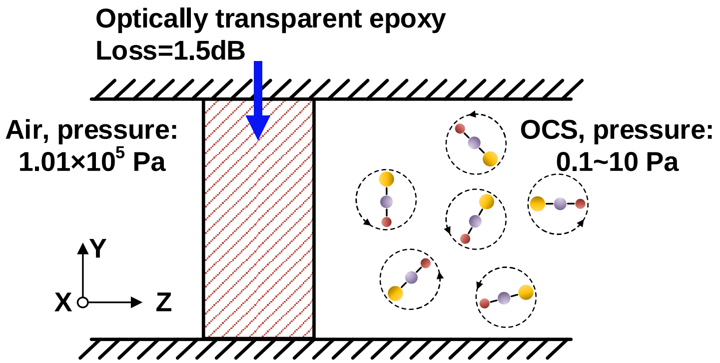
Measured S parameter

Optimum length

$$L_{opt} = \frac{1}{ln(10^{-\alpha_0/10})} \approx 14\text{cm}$$

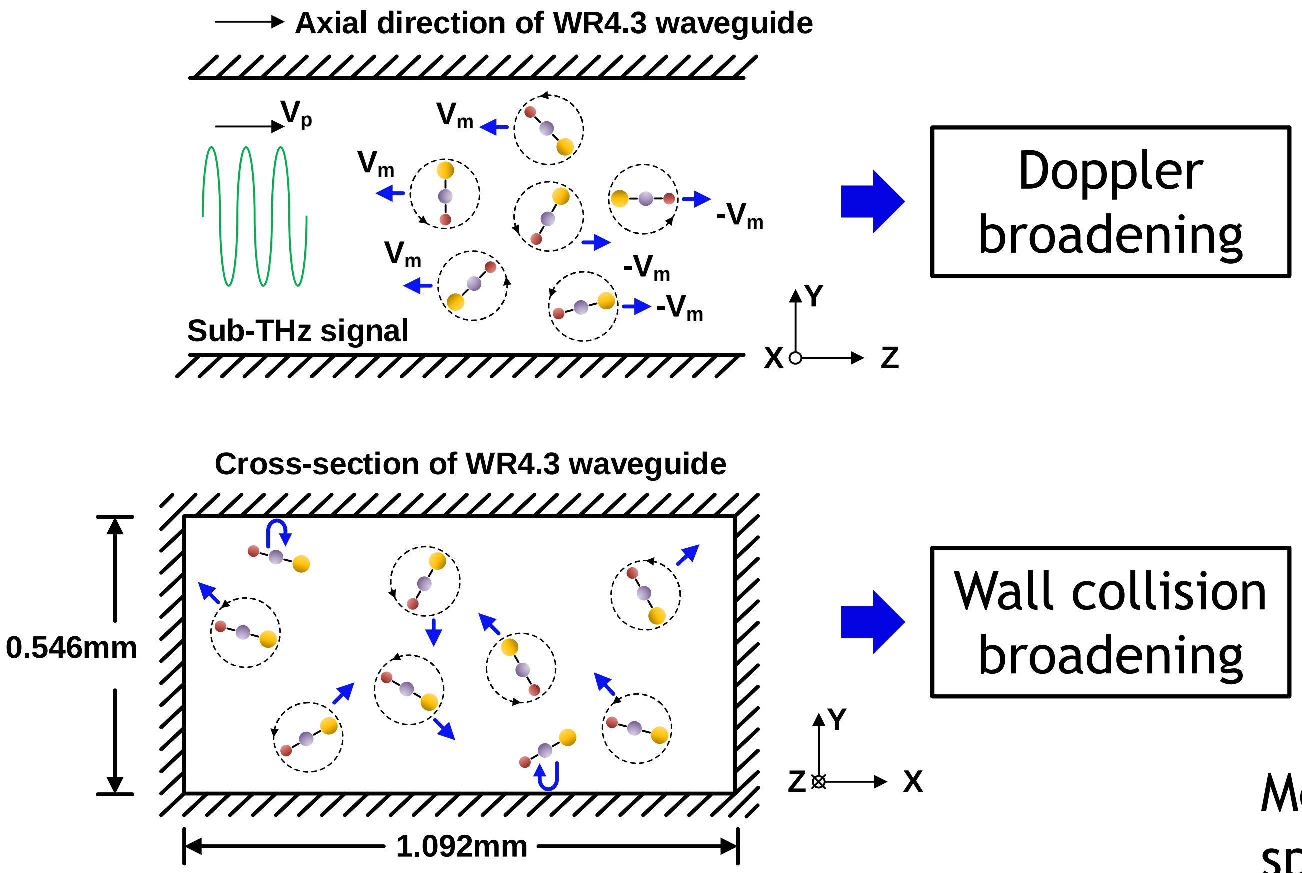
α_0 - Loss of waveguide, 0.2~0.3 dB/cm:

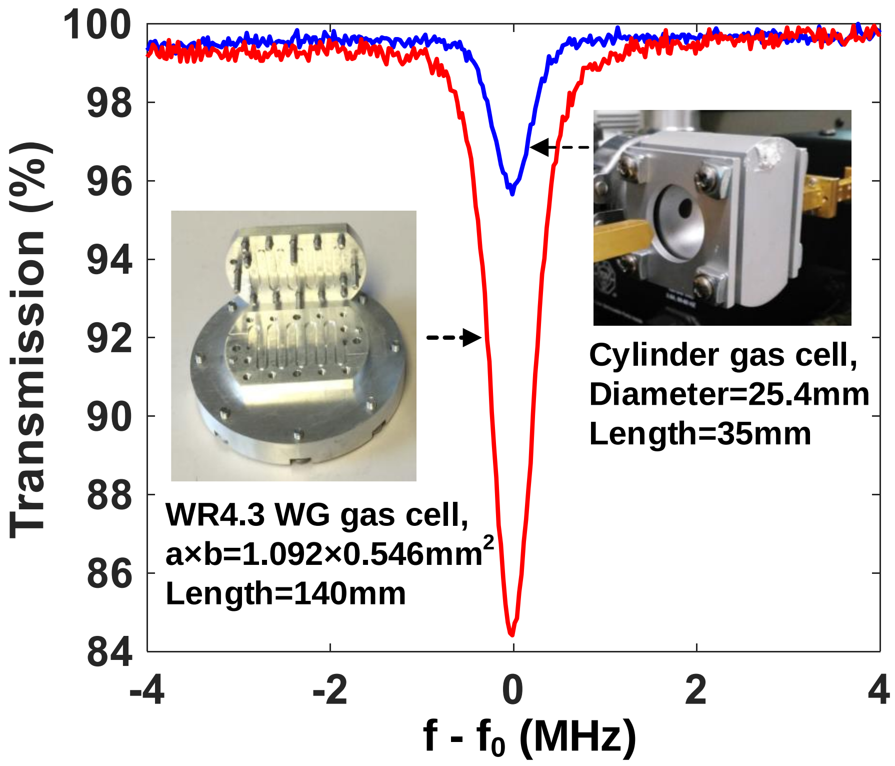
Vacuum sealing



Lorentz Line Profile in WR4.3 Waveguide Gas Cell

- **Doppler broadening:** the full width at half maximum (FWHM) is 534kHz.
- **Wall collision broadening:** slightly increases the FWHM by 7%.





Measured line profile of 267.530GHz (J=22←21) spectral line of OCS, Pressure = 1 Pa, P_{RF} = 1 μW

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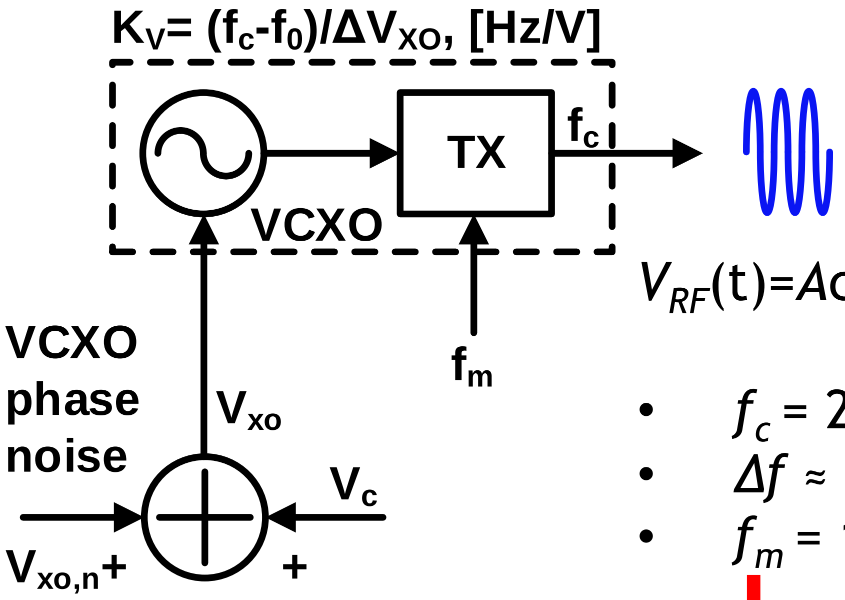
Wavelength Modulation Spectroscopy

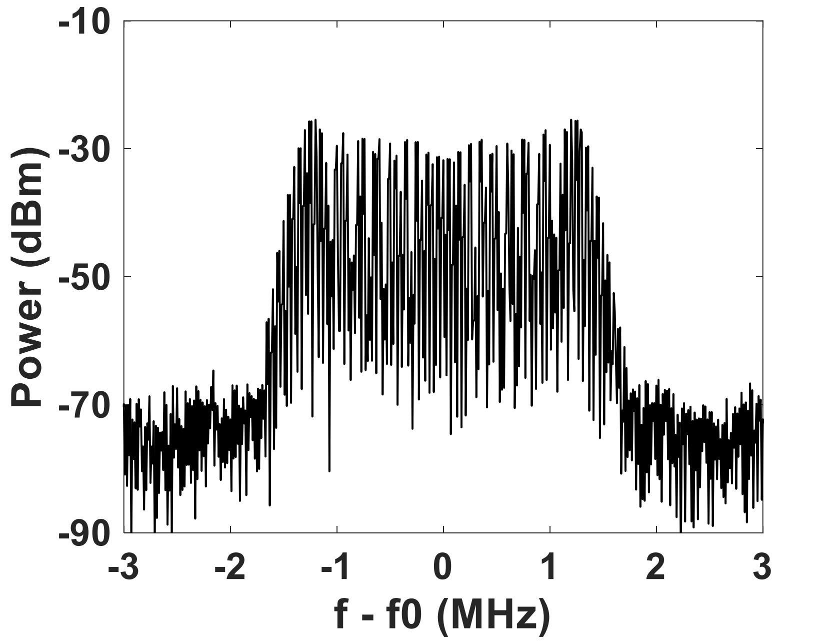


Wavelength-modulated sub-THz signal, $V_{RF}(t)$

$V_{RF}(t) = A\cos(f_c + \Delta f / f_m \times \sin(2\pi f_m t))$

- f_c = 267.530239GHz (J = 22←21)
- Δf ≈ FWHM
- f_m = 100kHz ≈ 0.1×FWHM

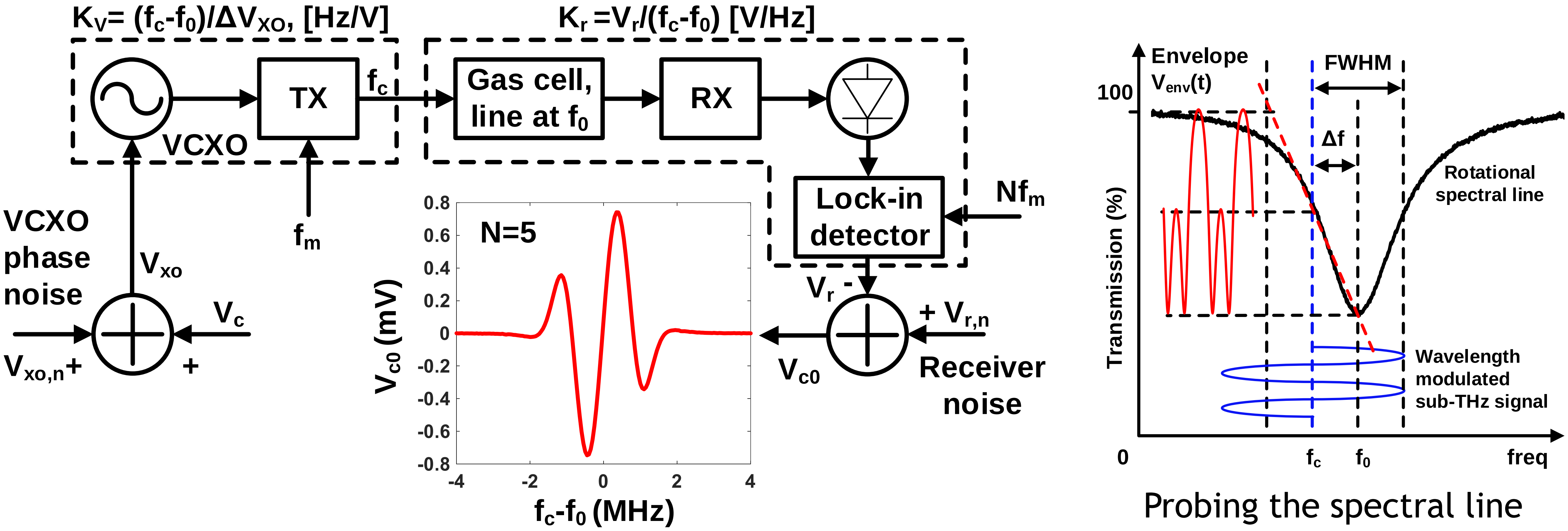
The modulation frequency f_m (hence the clock loop bandwidth) is limited by the absolute linewidth.



Measured spectrum of wavelength modulated signal at 267.530GHz

- Use wavelength-modulated signal for spectral line probing;
- THz front-end + voltage controlled crystal oscillator(VCXO).

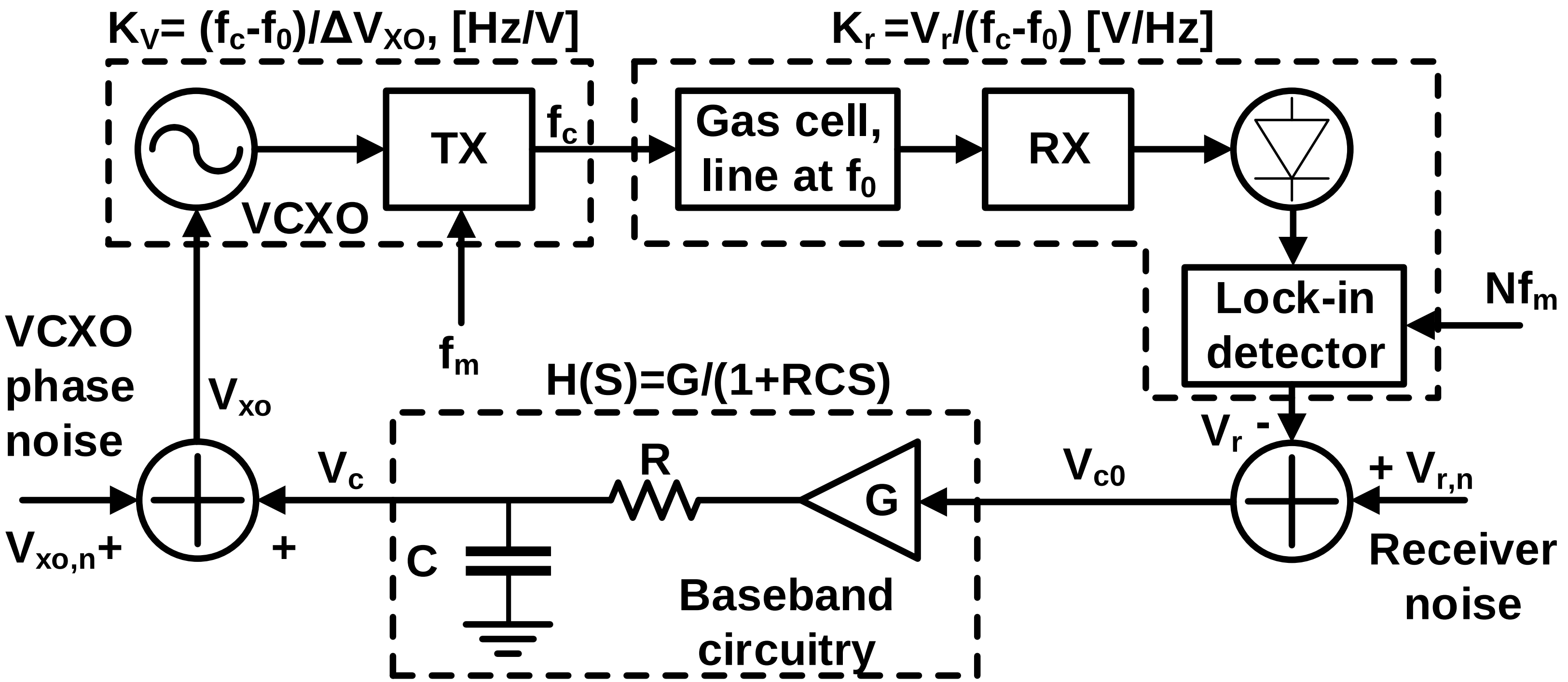
Wavelength Modulation Spectroscopy

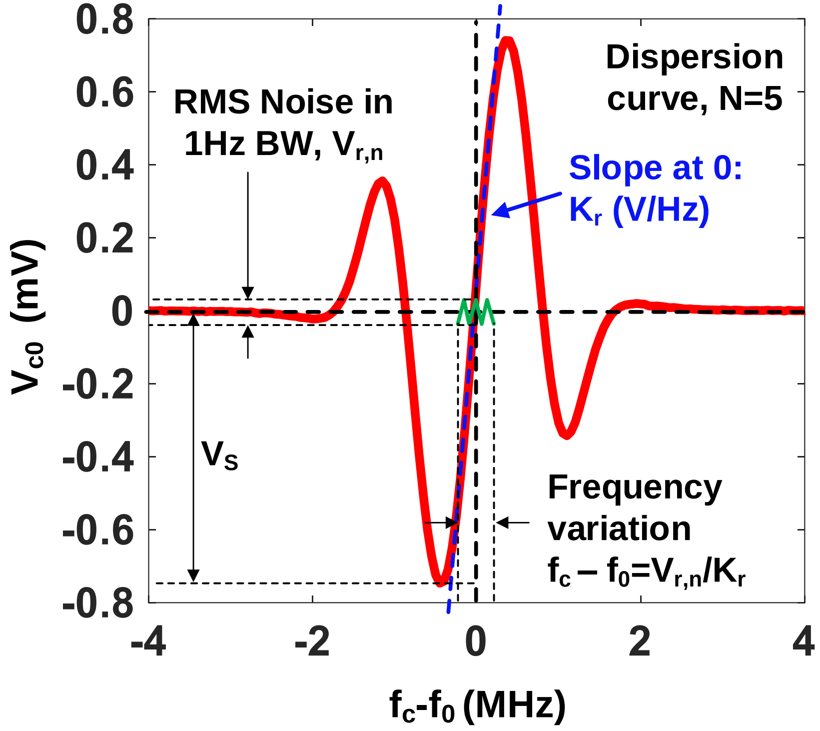


Probing the spectral line

- The sub-THz signal interacts with the OCS molecules in the WR4.3 gas cell;
- The 5th order harmonic dispersion curve is obtained by scanning f_c.

Clock Feedback Loop





Allan deviation (Frequency Stability)

Locking onto zero-crossing point

$$\sigma_y(\tau) = \frac{V_{r,n}}{\sqrt{2\tau} \cdot K_r \cdot f_0} \approx \frac{N_0}{Q \cdot SNR \cdot \sqrt{\tau}}$$

τ - Averaging time

Universal

Approximation

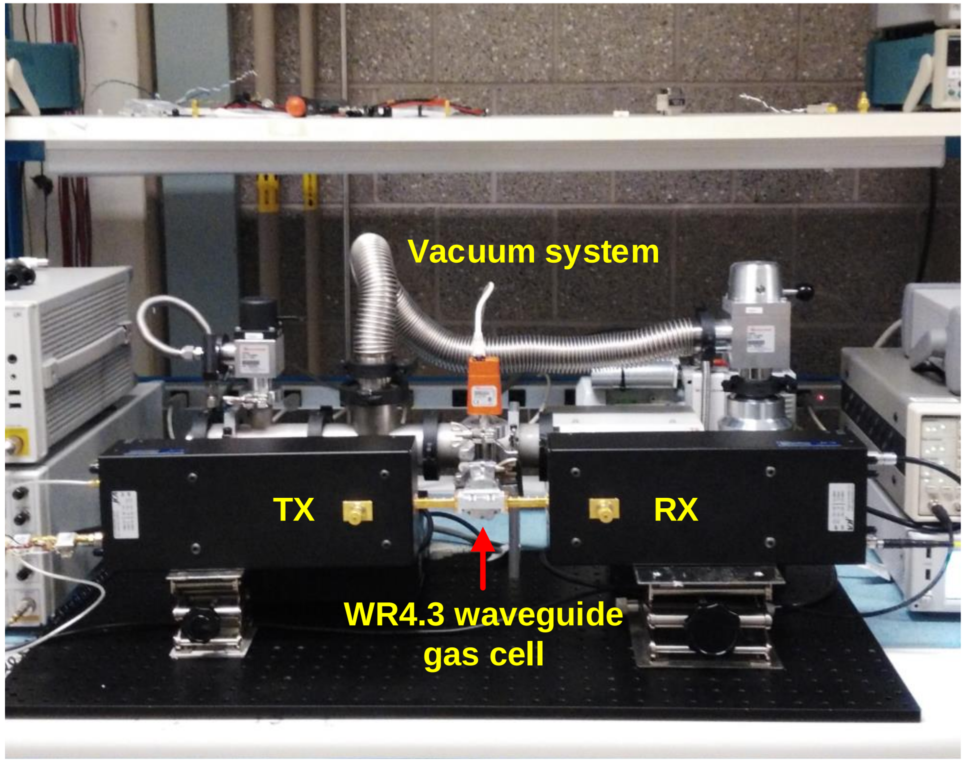
Quality factor

$$Q = \frac{f_0}{FWHM}$$

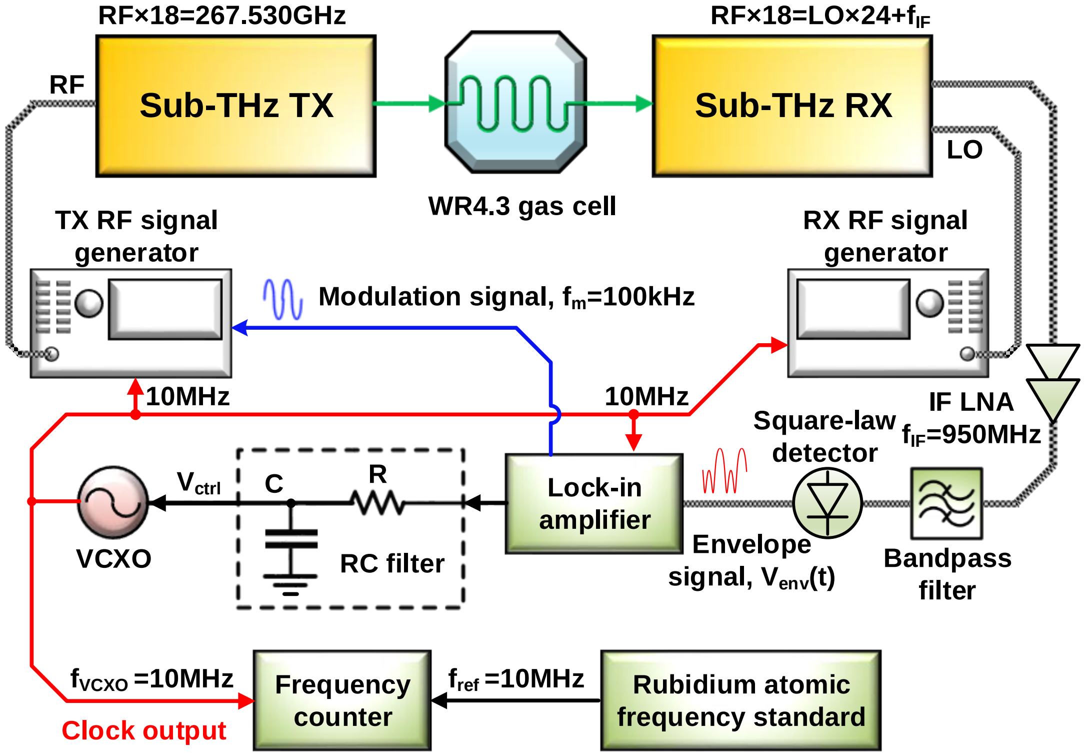
SNR in voltage (1Hz BW)

$$SNR = \frac{V_S}{V_{r,n}}$$

Lab-Scale Molecular Clock



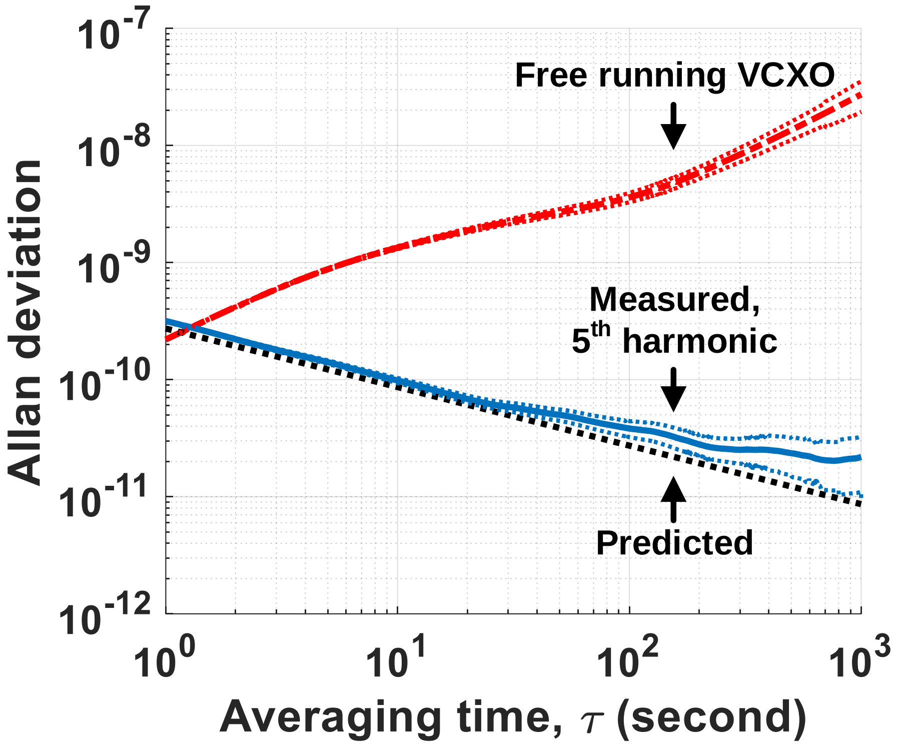
Photograph of lab-scale molecular clock



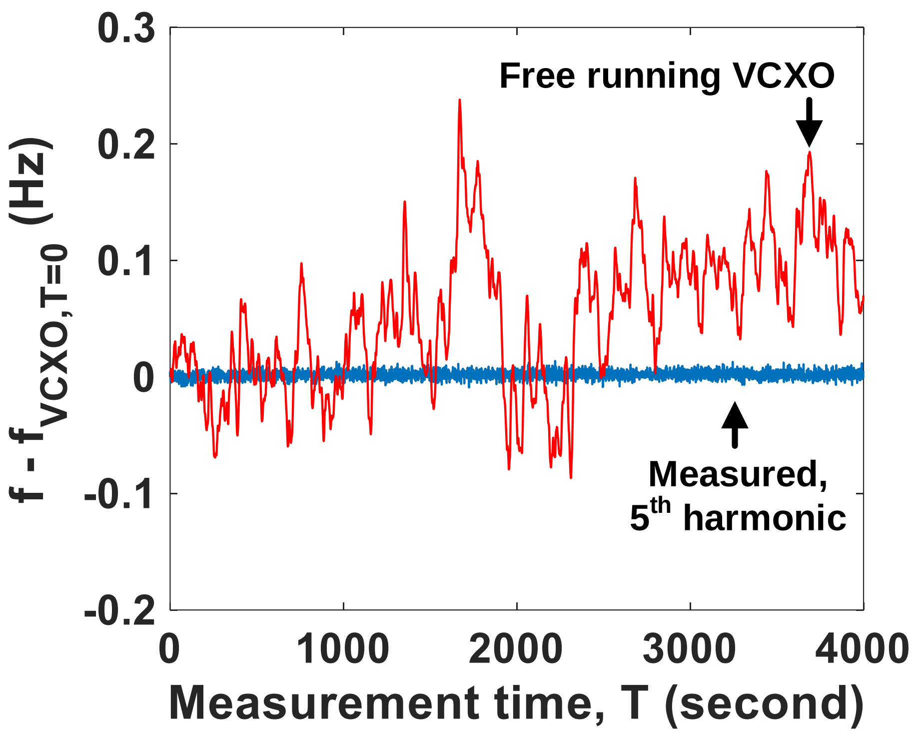
Schematic of lab-scale molecular clock

- VCXO + Keysight signal generator + VDI frequency extender;
- Measurement: frequency counter + Rb atomic clock.

Measurement Results of Lab-Scale Molecular Clock



ADEV locking to 5th har.



Instantaneous frequency over 4000s for 5th har. locking, averaging time =1s

- The measured Allan deviation (frequency stability): $\sigma_y(\tau=10^3 s)=2.2\times10^{-11}$;
- $10^3\times$ Improvement compared with the free running VCXO.

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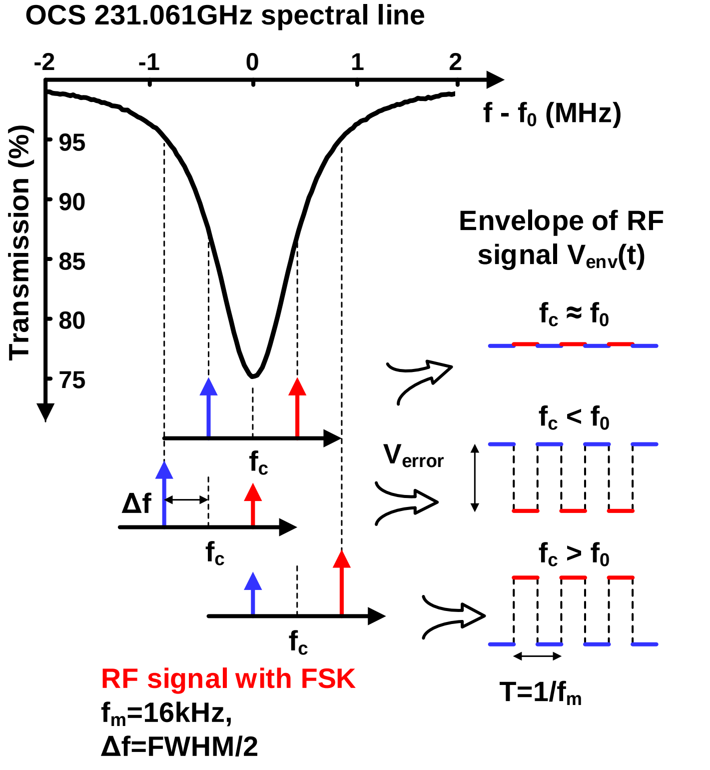
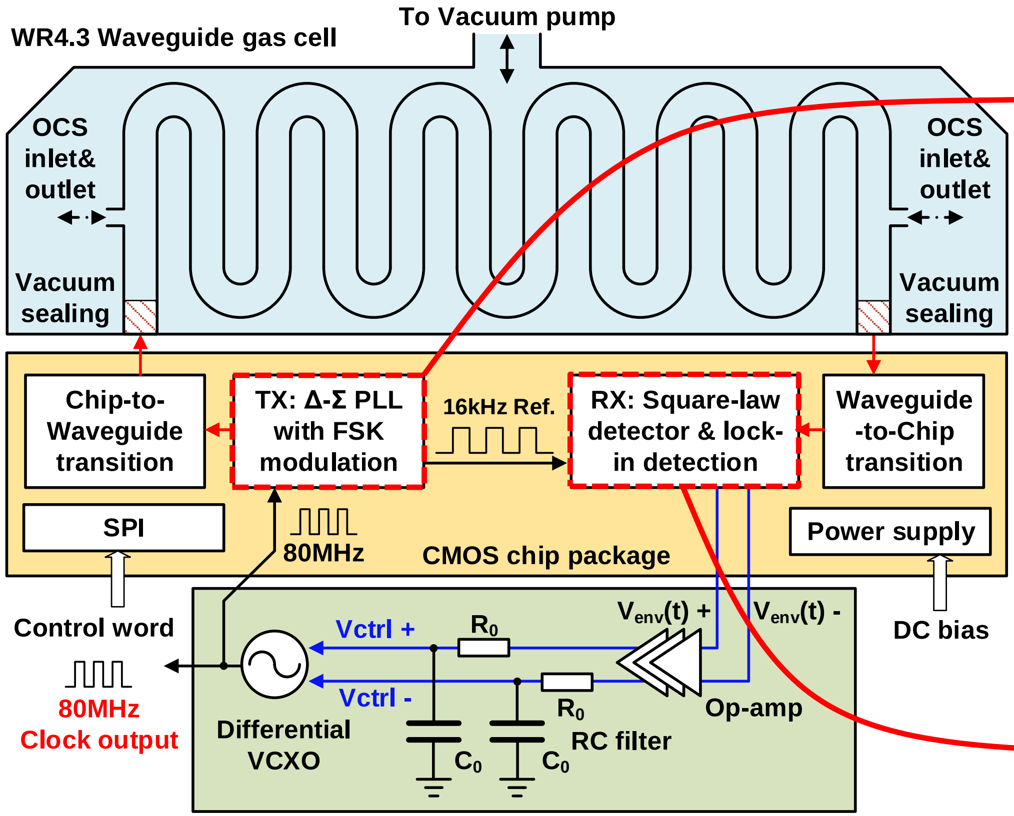
CMOS Molecular Clock: Architecture

- Utilize 231.061GHz (J=19←18) rotational spectral line of OCS for power saving.
- FSK modulation (16kHz) instead of analog wavelength modulation.

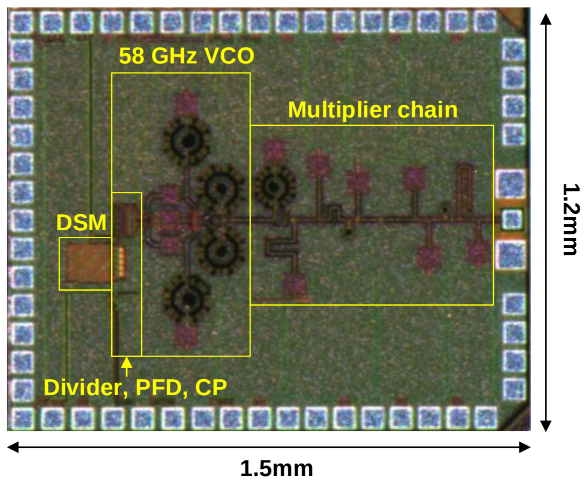


Spectral line probing using frequency-shift-keying (FSK)

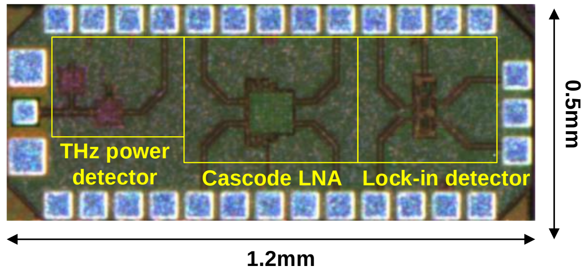


Architecture of CMOS molecular clock

TSMC 65nm LP process

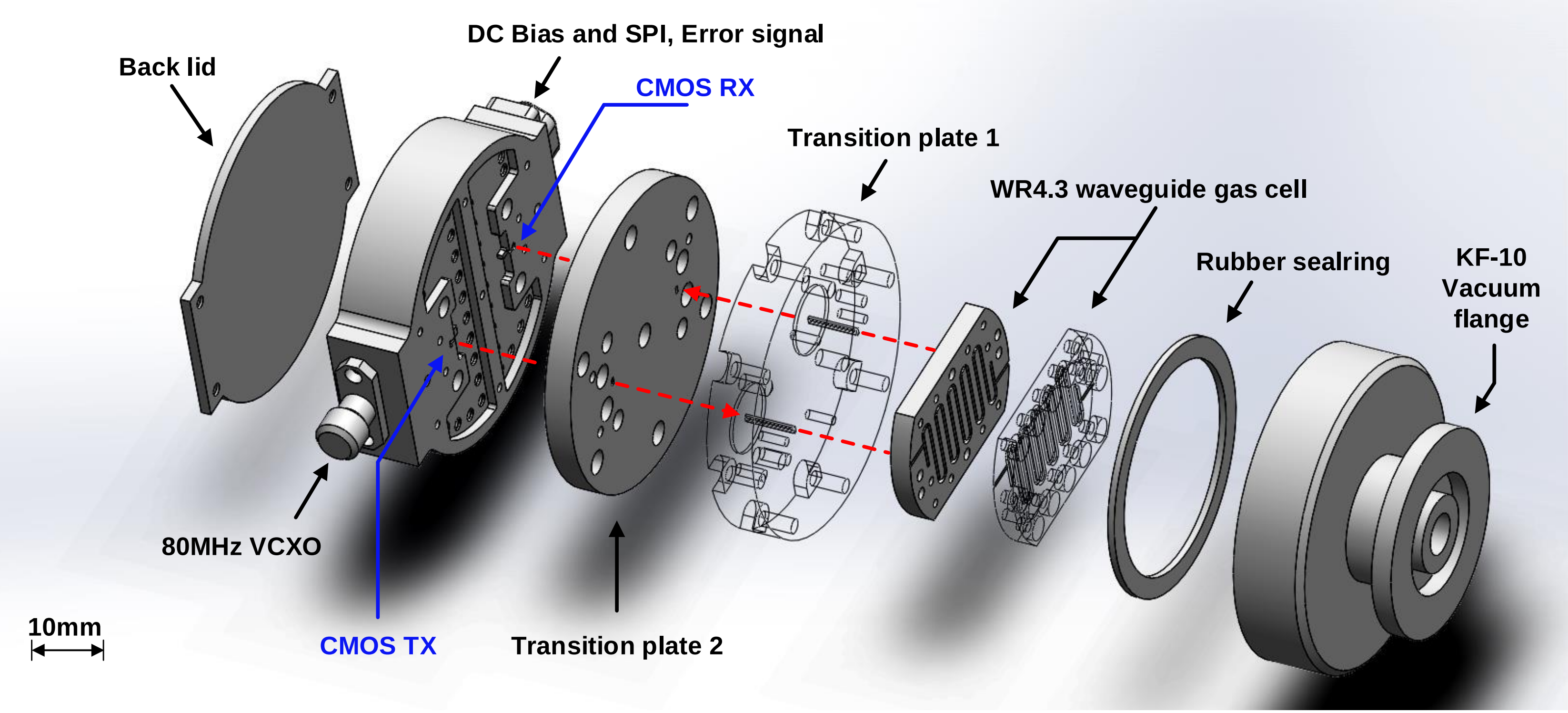


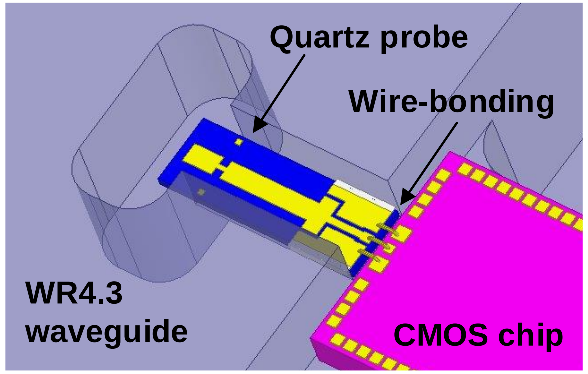
CMOS TX

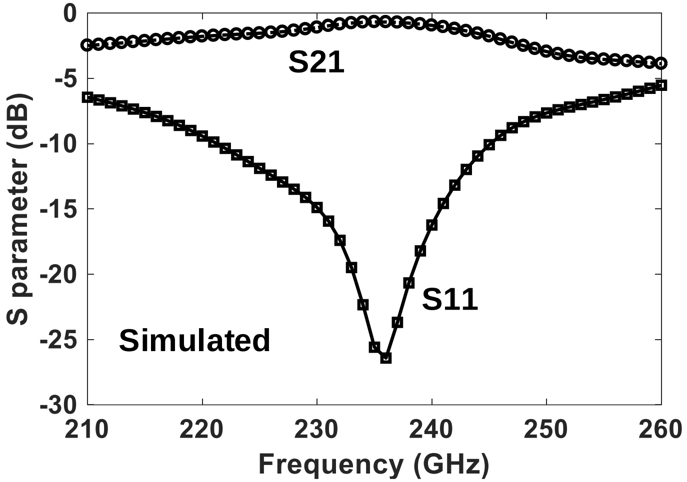


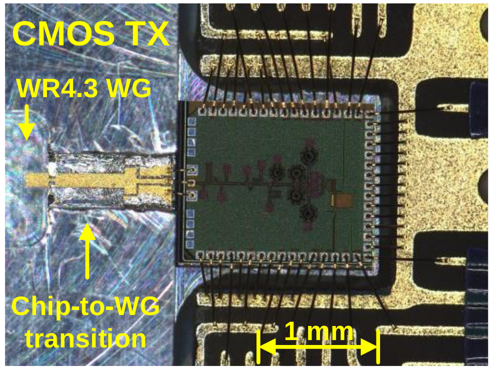
CMOS RX

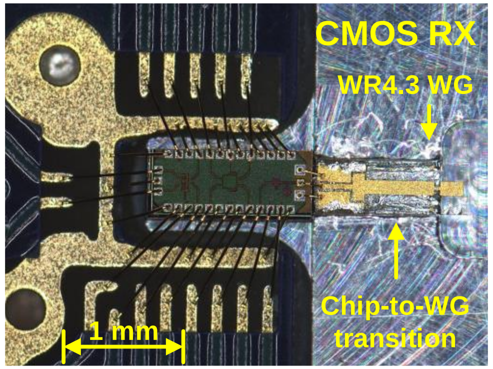
CMOS Molecular Clock: Packaging

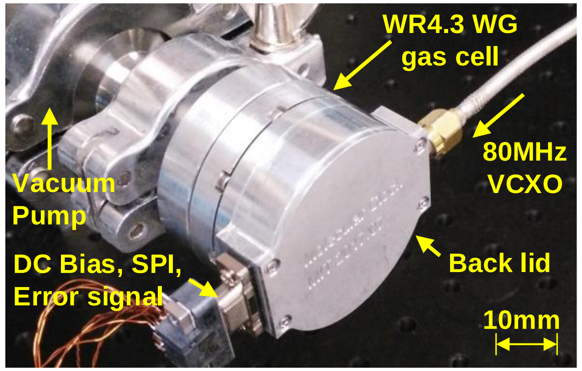








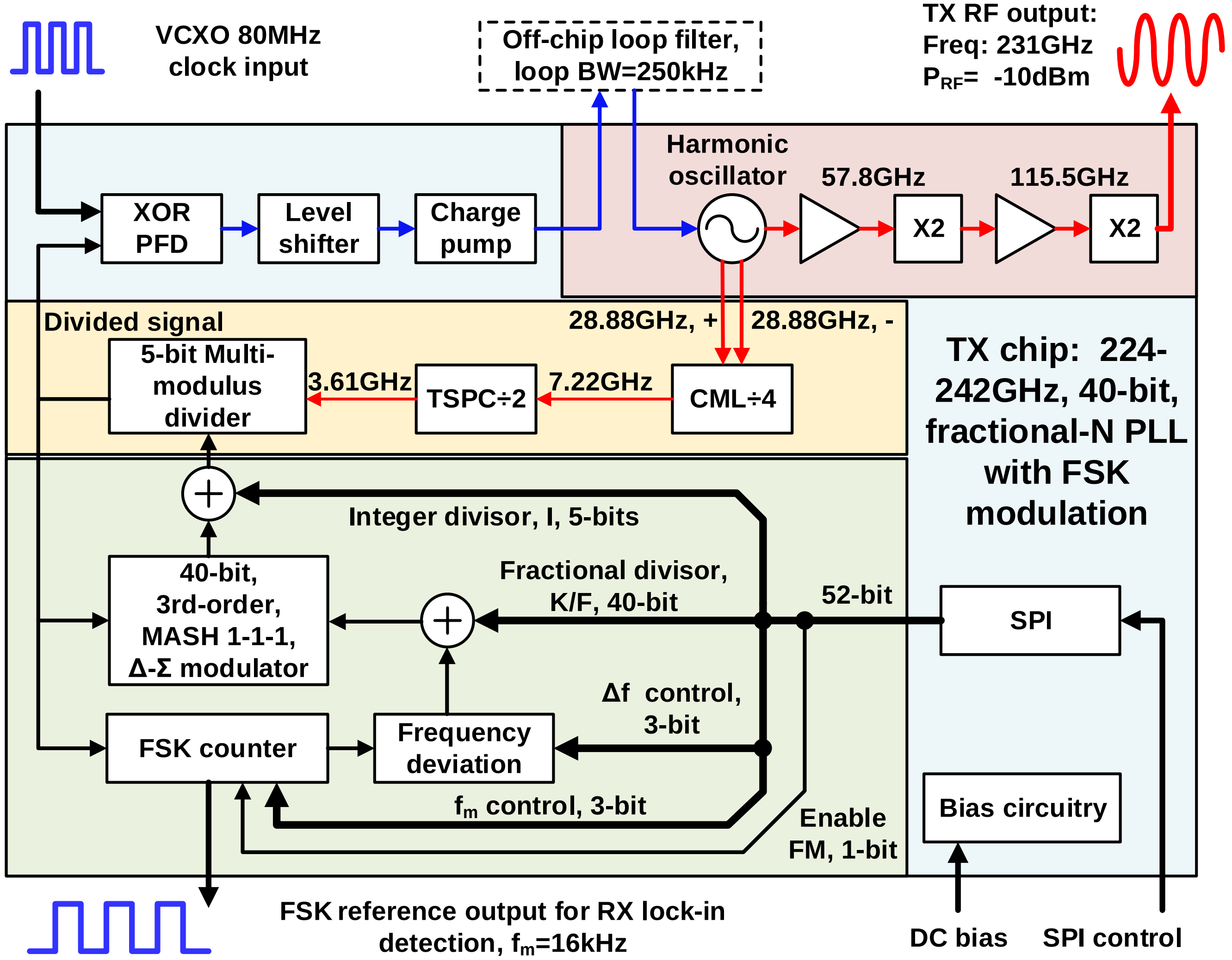




220-240GHz Chip-to-waveguide transition

- Measured loss: ~10 dB

CMOS TX: 224~242GHz, 40-bit Fractional-N PLL with FSK

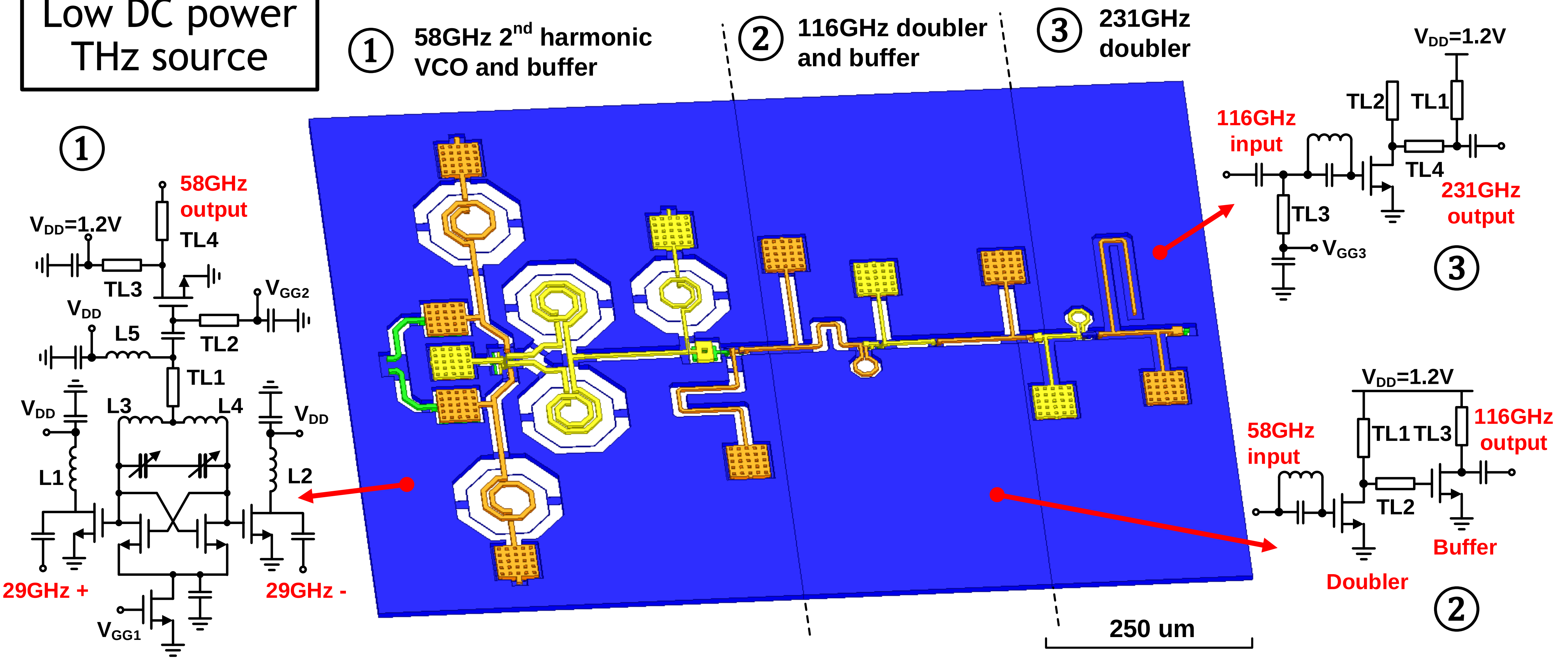


Technical Highlight

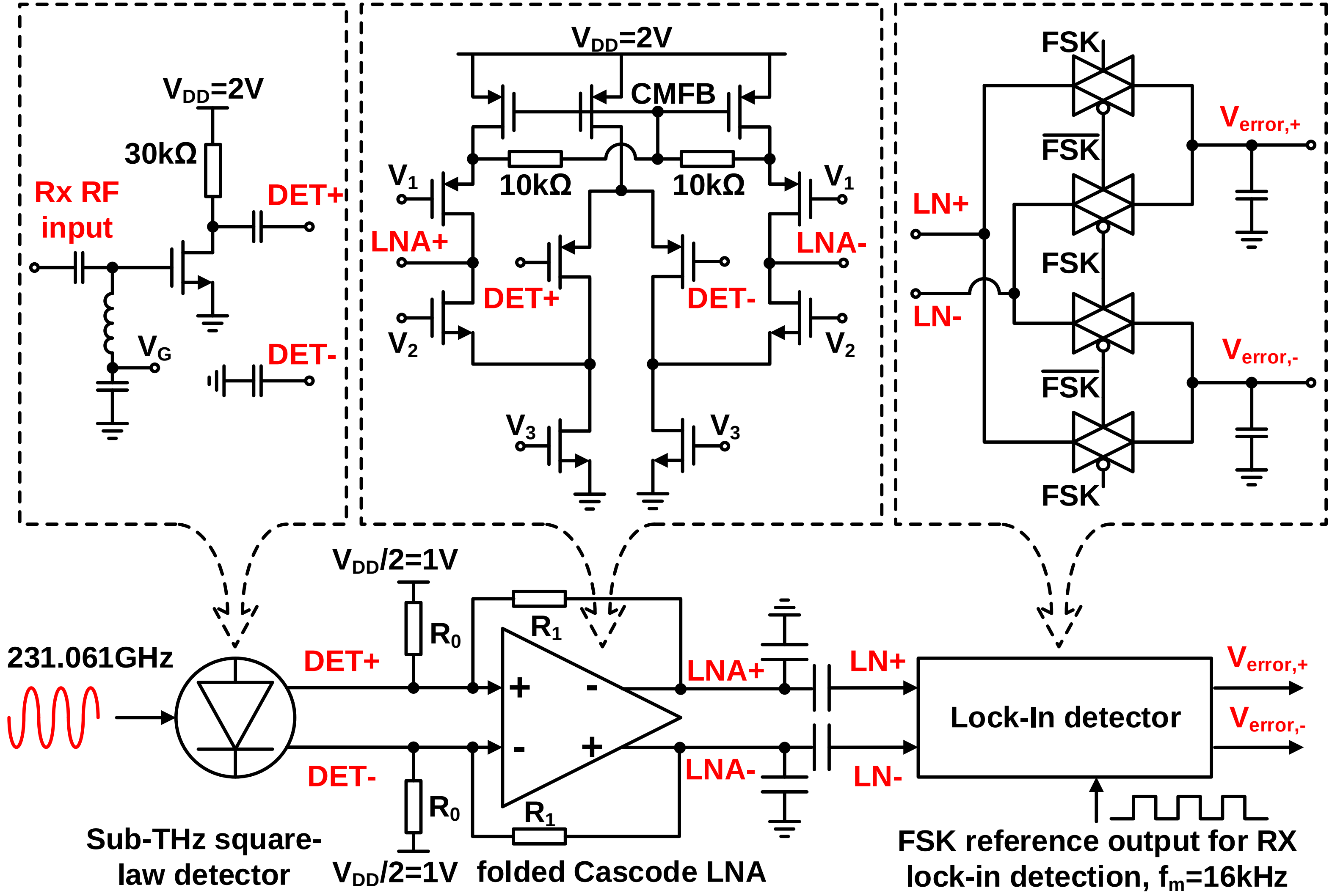
- High efficiency 2nd harmonic VCO and THz multiplier chain;
- 40-bit Δ-Σ modulator, ppt level (10^{-12}) frequency accuracy;
- FSK modulation, digitally controllable f_m and Δf;

CMOS TX: High Efficiency VCO and THz Multiplier Chain

Low DC power THz source



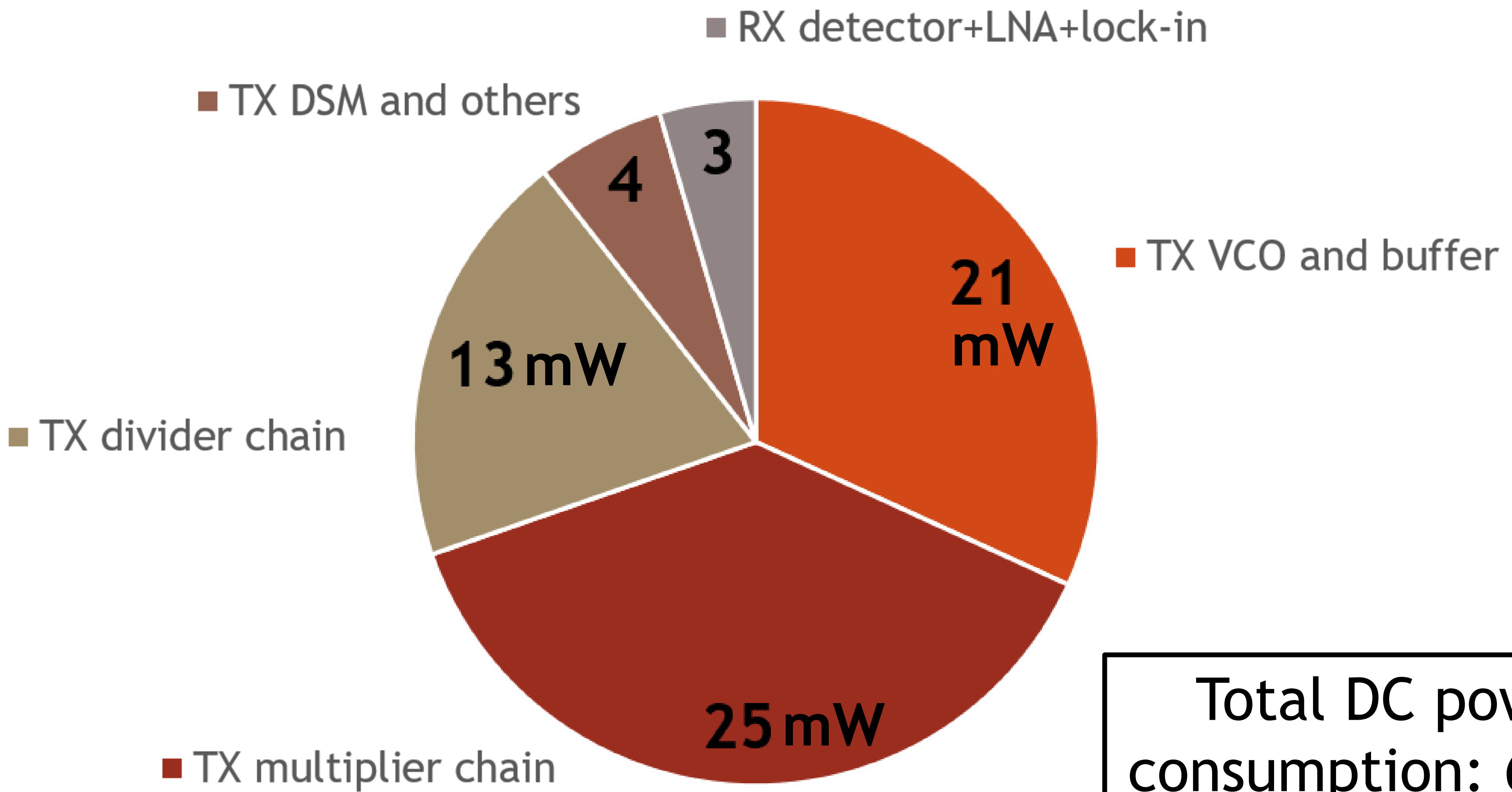
CMOS RX: 231GHz Detector with On-Chip Lock-in Detector



Technical Highlight

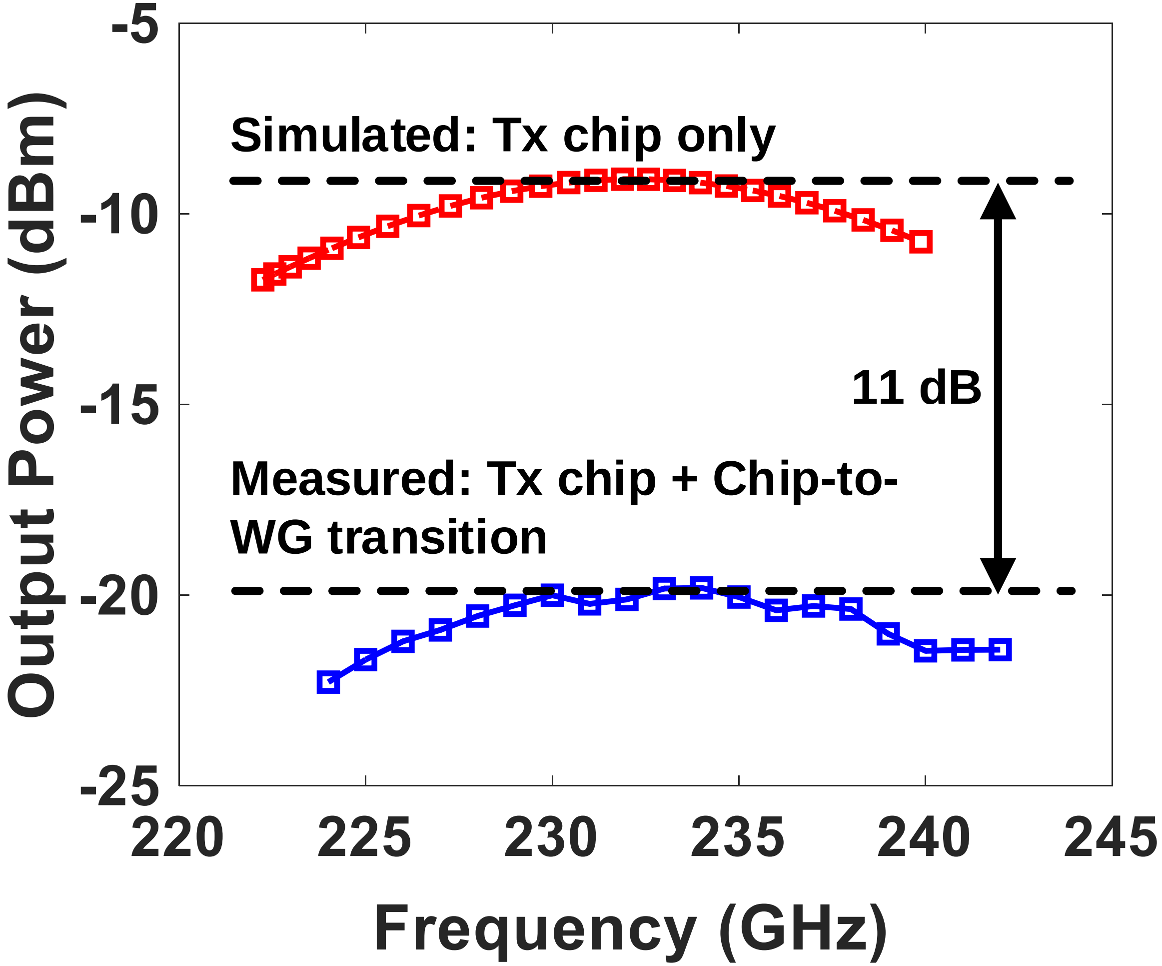
- 231GHz square-law detector based on sub-threshold NMOS transistor with flicker-noise reduction;
- Differential folded-Cascode baseband low noise amplifier;
- Transmission-gate based on-chip lock-in detector;

DC Power Consumption of TX/RX Chipset



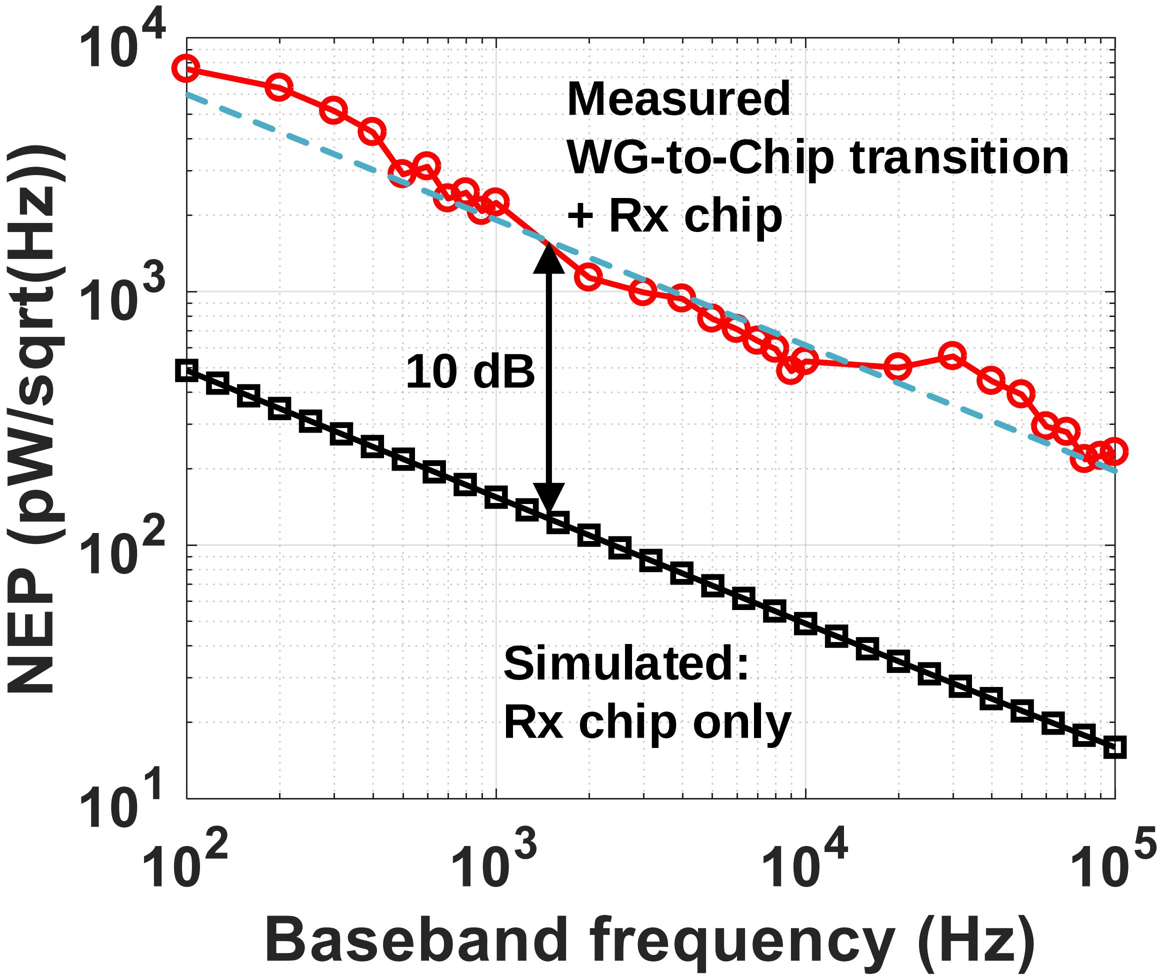
Total DC power consumption: 66mW

Measured Output Power of TX and NEP of RX



RF output power of TX

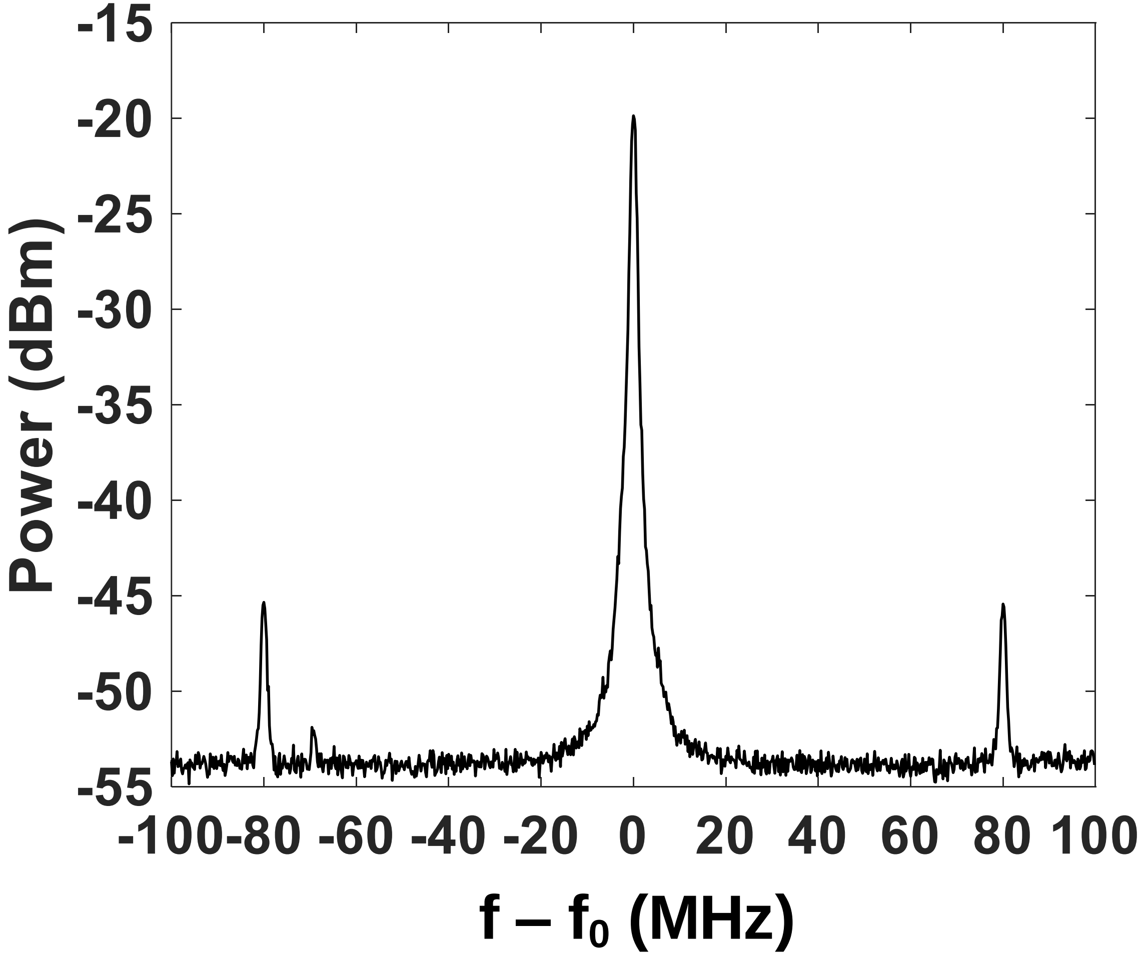
P_{out} = -20.2 dBm at 231GHz



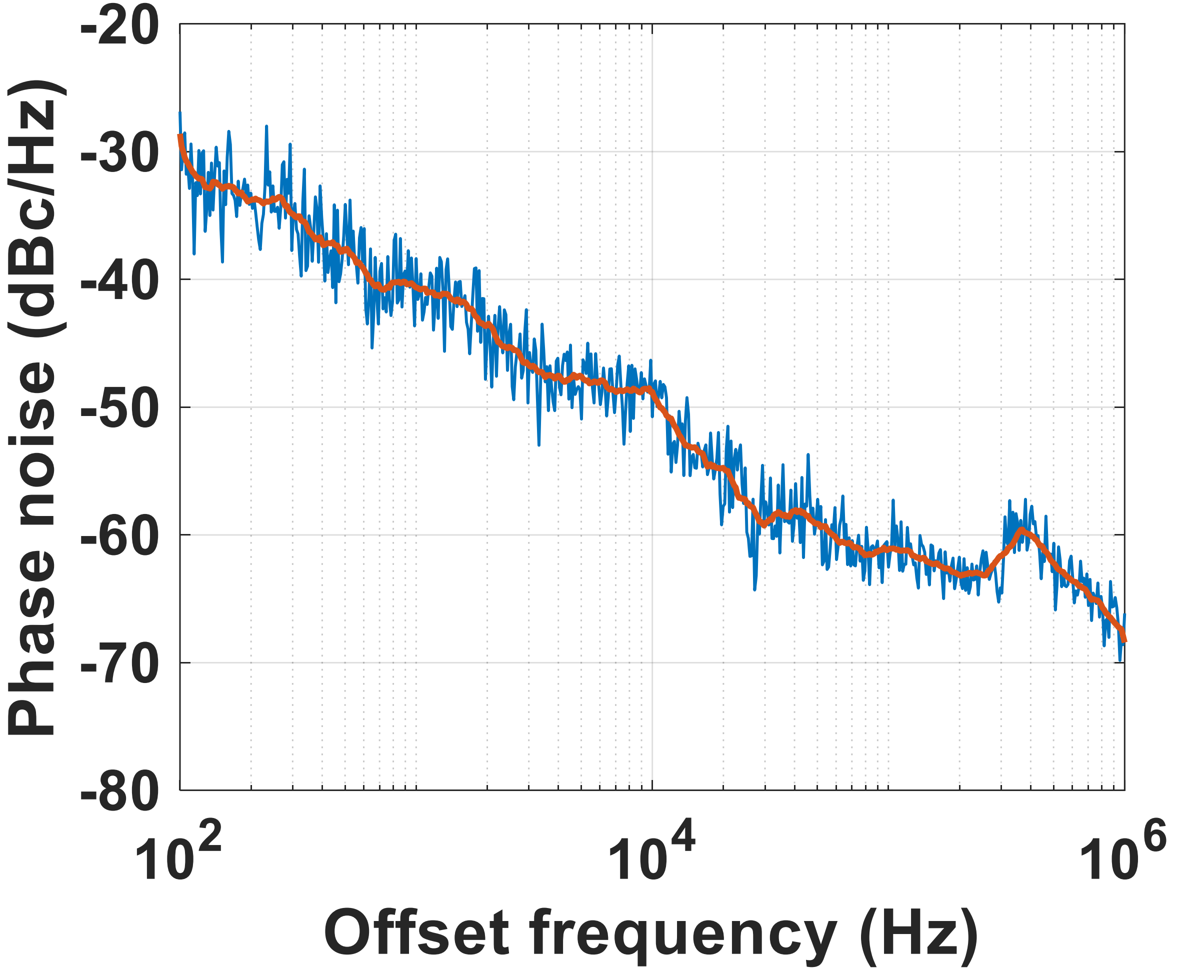
Noise equivalent power (NEP) of RX:

NEP = 501 pW/Hz$^{0.5}$@f_m=16kHz

Measured Output Spectrum and Phase Noise of TX



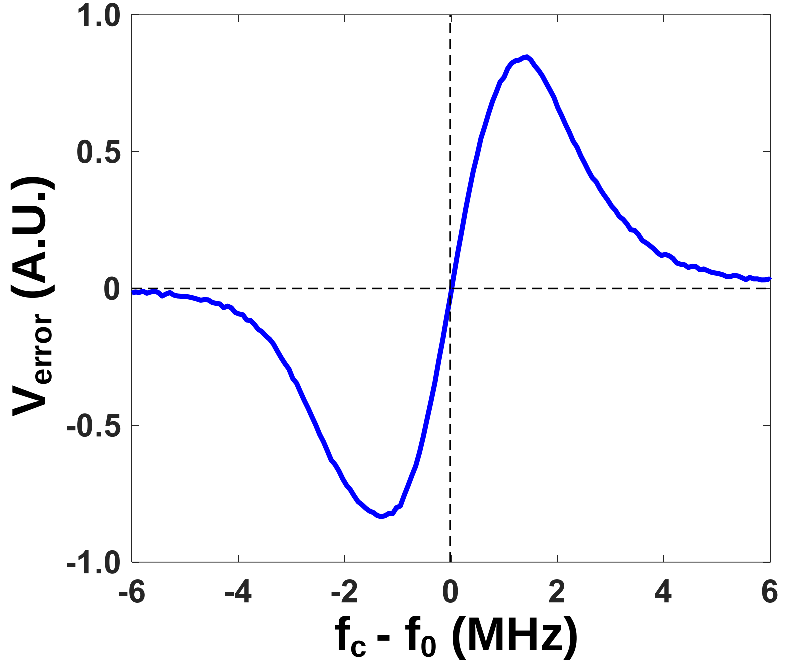
231GHz output spectrum



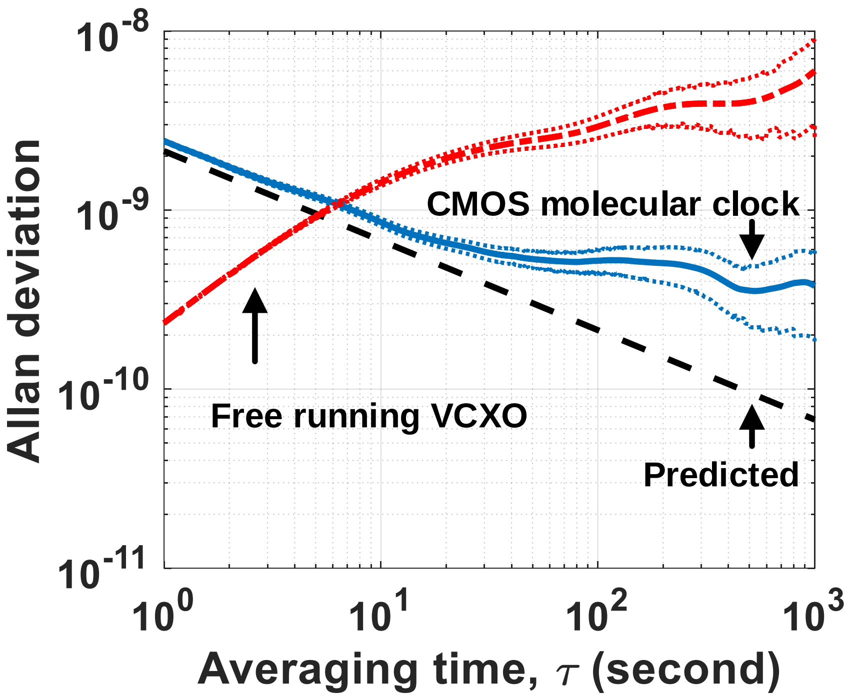
Phase noise of 231GHz signal:
-68.4 dBc/Hz@1MHz offset

Measurement Results of CMOS Molecular Clock

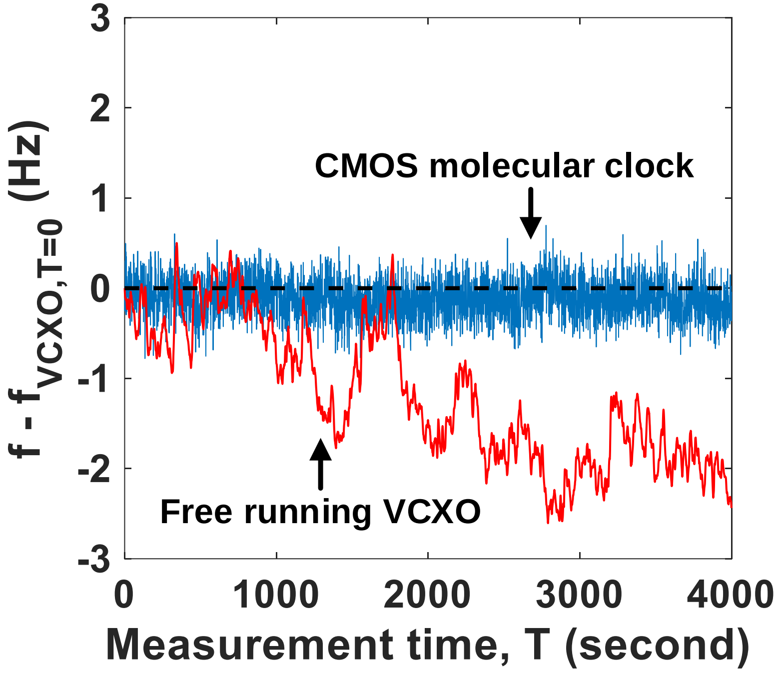
Fund. dispersion curve



Allan deviation



Instantaneous frequency



- Measured SNR with 1Hz BW is **445** (in voltage) or **53dB** (in power).

- ADEV $\sigma_y(\tau=10^3 s)=\mathbf{3.8\times10^{-10}}$;
- **10×** Improvement compared with free-running VCXO.

- Correct the drift of free running VCXO;
- 1s averaging time for each data point.

Performance Summary

	CMOS Molecular Clock	Lab-scale Molecular Clock
TX output RF power	-20 dBm*	-13 dBm
Modulation	16 kHz, FSK	100kHz, Wavelength modulation
Phase noise	-61.1 dBc/Hz @100kHz	-85.0 dBc/Hz @100kHz
RX noise	NEP: 501 $pW/Hz^{0.5}$ *	Noise figure:33 dB
Gas cell loss (dB)	7	7
Calculated SNR (dB)	57	92
Measured SNR (dB)	53	71
Stability $\sigma(\tau=1s)$	2.5×10^{-9}	3.2×10^{-10}
Stability $\sigma(\tau=10^3s)$	3.8×10^{-10}	2.2×10^{-11}

* Including 10 dB loss of chip-to-waveguide transition

- Gap between CMOS molecular clock and lab-scale prototype;
- Performance enhancement: loss reduction of package, phase noise optimization.

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Conclusion

- Molecular clock: a competitive candidate for highly-stable time-base generator for future portable devices.
- Perspective: array imaging, navigation and communication under GPS denied environment.

	Allan Deviation (10^3 s)	Linewidth (kHz)	$t_{turn-on}$ (second)	P_{DC} (mW)	Implementation
This Work	3.8×10^{-10}	880	<1	66[1]	65nm CMOS
CSAC [7]	3×10^{-10}	~1	N/A	26[2]	Electronics + Gas-Cell-Integrated Laser and Heater
CSAC [8]	1×10^{-11}	~1	180	120	

[1] The power of the VCXO is not included.

[2] The power of off-chip heater, laser, and other components is not included.

[7] D. Ruffieux, et al., ISSCC, pp. 48-49, Feb. 2011.
[8] Microsemi. QuantumTM, SA.54s chip scale atomic clock, 2017.

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