PRECISION TIMING

Molecular clock redux in miniature

Microwave transitions in the rotational spectrum of carbonyl sulfide molecules provide a timing reference that can be used to develop chip-scale atomic clocks.

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In 1948, the first atomic clock was demonstrated at the National Bureau of Standards, now the National Institute of Standards and Technology[1]. It was based on a microwave transition between two quantum-mechanically defined states in ammonia (NH_3) molecules in the gas phase. This early clock achieved a fractional frequency stability of only a few parts in 10^8 but ushered in a new era of atomic timing that continues to this day. Since then, significant advances have been made in atomic timekeeping, with the latest generation of laser-cooled optical atomic clocks[2] reaching overall fractional frequency stabilities near 1 part in 10^{18}. At the same time, considerable progress has been made in the development of miniaturized, low-power atomic clocks. Chip-scale atomic clocks[3] (CSACs), for example, are made using silicon micromachining techniques and operate with thirty times lower power consumption than any previous atomic clock. They are bringing atomically precise timing to portable, battery-operated systems such as GPS receivers[4] and underwater seismic sensing for oil exploration[5]. Writing in *Nature Electronics*, Ruonan Han and colleagues at Massachusetts Institute of Technology now revisit the approach used in the first atomic clocks, but with the help of modern technology and engineering, and with a focus on miniaturization[6]. Instead of ammonia, they probe the gaseous linear molecule carbonyl sulfide (OCS) and are able to create a table-top package with a frequency stability comparable to that of a commercial CSAC. They also develop a compact system with integrated complementary metal–oxide–semiconductor (CMOS) electronics that is shown to run on less than 100 mW of electrical power.

In passive atomic clocks, a high-frequency signal, usually derived from a quartz crystal oscillator, is locked to an atomic resonance, thereby stabilizing the oscillator to the atoms. Since the transition frequencies in atoms and molecules are determined largely by fundamental constants, such clocks possess intrinsic accuracy and can achieve exceptional long-term frequency stability.

Han and colleagues have explored a new frequency regime in atomic and molecular standards, which is possible due to the considerable advances that have been made in high-frequency CMOS electronics over the past few decades. In particular, they examine microwave transitions in carbonyl sulfide in the 200–300 GHz band, which drive changes in the rotational quantum state of the molecules. These transitions have significant advantages over similar ones in ammonia, which are near 20 GHz. The higher resonance frequency implies more oscillations can be counted in a fixed period, leading to finer timing resolution, whereas the stronger molecular absorption results in larger absorption signals and improved signal-to-noise ratio. Additionally, the higher resonance frequency also means

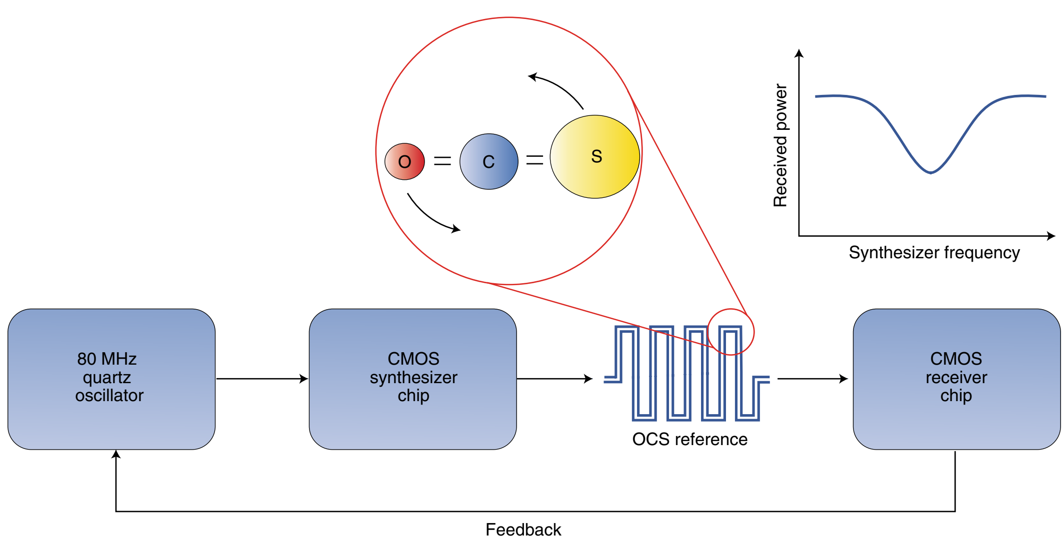

Fig. 1 | **Carbonyl sulfide molecular clock architecture.** An 80 MHz signal from a quartz oscillator is multiplied to above 200 GHz using a compact, low-power CMOS synthesizer chip. This microwave field interrogates a sample of carbonyl sulfide (OCS) confined in a small waveguide and the microwave power transmitted through the molecular gas is detected with a CMOS receiver. The absorption resonance is used to lock the oscillator to the molecular transition and stabilize it accordingly that the radiation wavelength is smaller and can be confined in a correspondingly smaller waveguide. Han and colleagues take advantage of all these desirable features.

The researchers report two implementations of their new clock. The first emphasizes performance and is constructed from larger components to achieve the highest stability. A microwave signal generated by a frequency-multiplied synthesizer is sent through a meandering waveguide filled with carbonyl sulfide gas. The transmitted radiofrequency power is detected and shows clear absorption resonances as the microwave frequency is scanned near the carbonyl sulfide absorption line frequency. They use this clock to investigate and assess the stability limits, reaching a short-term stability comparable to a commercial chip-scale atomic clock. In the second implementation, the microwave transmitter and receiver were fabricated in a CMOS, thus allowing the size and power consumption to be reduced considerably (Fig. 1). Of course, further work remains to be done in order to create practical devices, particularly with respect to the size of the vacuum package containing the carbonyl sulfide and in assessing the long-term frequency stability of the device. But the work of Han and colleagues clearly demonstrates the fundamental viability of such a system and may lead to other new innovations in molecular microwave spectroscopy.

Compact, low-power atomic clocks are becoming an important tool for maintaining precise time in portable, battery-operated systems. Carefully synchronized underwater seismic sensors, for example, play an important role in oil exploration by detecting seismic waves reflected off rock strata beneath the ocean floor. Wireless telecommunications systems require microsecond-level timing or better to enable efficient transfer of data across distributed networks. And the inclusion of a precision clock within a global navigation satellite system receiver can result in considerable benefits, including higher resistance to jamming and lower positioning error. The further development of compact, low-power clocks, such as that developed by Han and colleagues, is sure to result in new capabilities and enhanced performance across a broad range of technology sectors. ❐

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