4.5 Towards Chip-Scale Atomic Clocks

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The performance of many electronic systems is often limited by the performance of the clocks they use. For example, a receiver in the Global Positioning System (GPS) works by attempting to align an internally generated pseudorandom signal to an identical signal sent by a satellite and measuring the phase difference between the two. The receiver then calculates the time required for the satellite signal to reach the receiver, and thereby gives the distance between the satellite and the receiver. In this system, accurate timing is needed not only for precise determination of distance, but also for fast acquisition of the satellite signal and resistance against jammers. Countless other examples can be cited where timing determines the ultimate performance of a system, from parallel A/D converters, to spread-spectrum communications. In such applications, atomic clocks could greatly enhance the performance of the system. Unfortunately, however, the size and power consumption of atomic clocks has been prohibitively large for many portable applications.

Pursuant to solving this problem, a miniature physics package for a chip-scale atomic clock is demonstrated in this paper. The physics package, shown in Fig. 4.5.1, includes a tiny micromachined cesium (Cs) atomic vapor cell [1], an 852nm VCSEL, a photodiode detector, polarizing and focusing optics, heater elements to maintain Cs atoms in a vapor state, and a micromechanical suspension system that thermally isolates the vapor cell/heater structure to allow elevated temperatures with low-power consumption. The system is implemented in a MEMS-enabled size less than 10mm^3, which is more than 700× smaller in volume than the smallest atomic clock physics package in production. At present, the control and microwave local oscillator electronics for this atomic clock are off-chip, but work to integrate them onto a similar size scale is ongoing. With off-chip electronics, a complete atomic clock using this prototype physics package achieves an Allan deviation frequency stability of 2.4×10^{-10} at an integration time of 1 second, which satisfies the 1 second goal of DARPA's Chip-Scale Atomic Clock (CSAC) program. The clock, however, does not yet satisfy the longer term 1 hour CSAC goal of 1×10^{-11}. In addition, the physics package consumes 75mW of power, which is 100× better than the present lowest power production atomic clock, but still much higher than the 30mW CSAC total clock power goal (implying a need for ~10mW for the physics package). Both the 1 hour stability and power consumption goals will likely require a more sophisticated integrated environmental control system.

Like quartz oscillators and clocks, atomic clocks function by generating a very stable frequency from a stable reference. The main difference is that a quartz oscillator derives its frequency from a mechanically vibrating reference, which makes the frequency sensitive to long-term changes in mechanical dimensions and stress. An atomic clock, on the other hand (Fig. 4.5.2), derives its frequency from the energy difference between the hyperfine states of an alkali metal atom, which is a constant of nature, and thereby, much more predictable and stable. Unfortunately, however, the alkali metal atoms must be maintained at sufficient density in a vapor state to operate the atomic clock. This means excess power must be consumed to heat the atomic vapor cell. For a tabletop atomic clock, this takes tens of watts of power. But when one shrinks the atomic cell to less than 10mm^3 using the MEMS technology, the amount of power needed to keep the atoms in a vapor state can be reduced to less than 10mW in a properly designed thermal control system. In effect, the smaller the mechanical structure, the less power is needed to heat up to a given temperature.

As shown in Fig. 4.5.3, which depicts the anatomy of a gas cell atomic clock, the physics package represents only one important part of an atomic clock. The electronics for the microwave oscillator and for environmental control are equally important. In particular, although an atomic cell can generate a resonance with exceptional long-term stability, its effective short-term stability is somewhat poor, since the output power of the cell is very low. To remedy this, an atomic clock frequency locks a microwave oscillator to the frequency of the atomic cell (6.8GHz for Rubidium, 9.2GHz for Cesium) and uses the microwave oscillator output (or a divided-down version for lower output frequencies) as its higher power output. To insure sufficient stability to allow locking in the first place, the microwave oscillator often consists of a microwave VCO phase-locked to a voltage-controllable crystal oscillator in a phase-locked loop. This is a rather power hungry configuration, given the large divide-down ratio needed to lock these two oscillators. In particular, the hundreds of mW generally needed for such an oscillator is already several times higher than the 30mW goal. Allotting 10mW each to cell heating and environmental control electronics, a microwave oscillator running with only ~10mW of power is needed.

To reduce the power consumption while retaining the high-Q and temperature stability of a crystal-referenced oscillator, many researchers are turning to micromechanical resonator technology, which to date has achieved vibrating on-chip mechanical resonators with frequencies past 1.5GHz [2], exhibiting Q's greater than 10,000 (Fig. 4.5.4), even when operating in air (as opposed to vacuum) [3]. Micromechanical resonators have also been demonstrated with temperature coefficients down to –0.24ppm/°C, which is well within the requirements for locking to an atomic cell. Since neither phase locking of two oscillators nor frequency division would be needed for a VCO based on a voltage-tunable micromechanical resonator, such an oscillator should be able to achieve excellent stability with power consumption less than 1mW, and in a size smaller than 100×100μm^2, including transistor circuits and the resonator.

Examples of such oscillators at lower frequencies are already being implemented [4][5]. Figure 4.5.5 presents the schematic for an oscillator that combines a custom IC sustaining amplifier with a wine-glass-mode disk resonator capable of achieving on-chip Q's up to 145,000. This oscillator consumes only 330μW to attain measured phase noise densities (shown in Fig. 4.5.6) of –125dBc/Hz at 1kHz offset and –147dBc/Hz far from the carrier, which practically satisfy GSM reference oscillator specifications. Versions with atomic clock-amenable frequencies are expected soon.

If a 10MHz clock output is still needed, then frequency division will be required. In this case, low-power frequency division will again be a challenge. However, since the frequency tuning requirements of the microwave oscillator in an atomic clock are far less demanding than that of frequency synthesizers used in wireless applications, there are design techniques that might be available to divide down to 10MHz without consuming significant power. The work in these areas is ongoing.

References:

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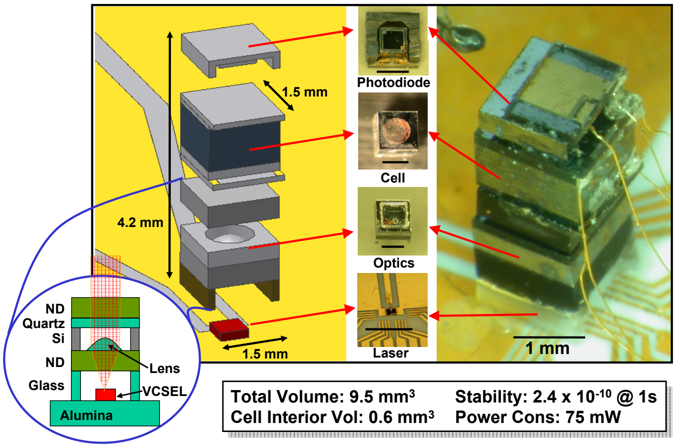

Figure 4.5.1: Schematic and photo of a tiny atomic physics package used in a chip-scale atomic clock.

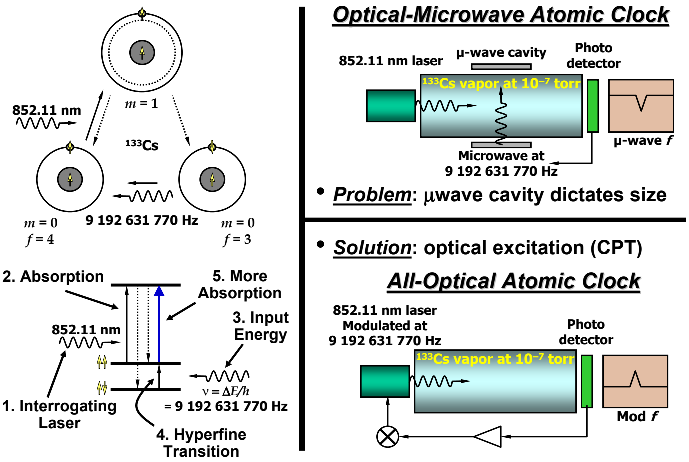

Figure 4.5.2: Physics and implementation strategies for small atomic clocks, where the output frequency is determined by the energy of an atomic transition.

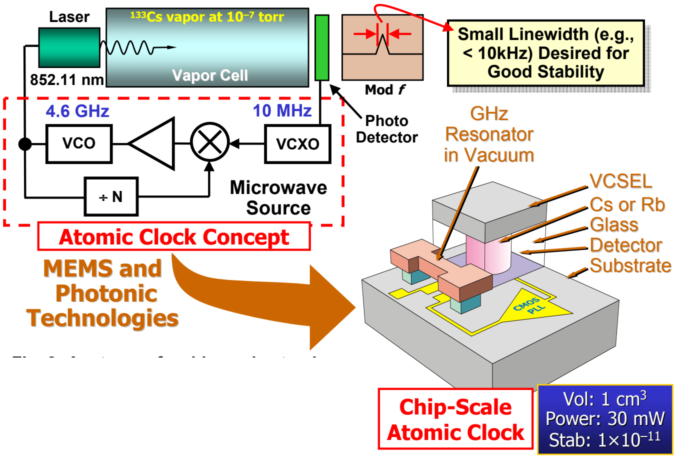

Figure 4.5.3: Anatomy of a chip-scale atomic clock. To date, tiny cells and gigahertz reference resonators have been successfully demonstrated with high Q, and low power oven control has been achieved. Control and oscillator circuit power consumption remain as bottlenecks to the 30mW goal.

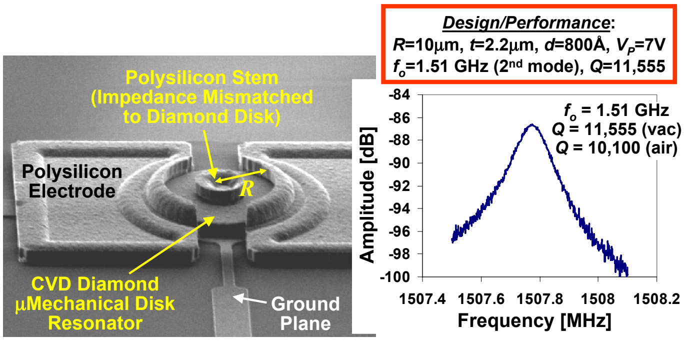

Figure 4.5.4: Scanning electron micrograph (SEM) and measured frequency characteristic for a 1.51-GHz polydiamond micromechanical disk resonator. The measurement was performed without matching to the network analyzer, so the amplitude is not indicative of actual loss.

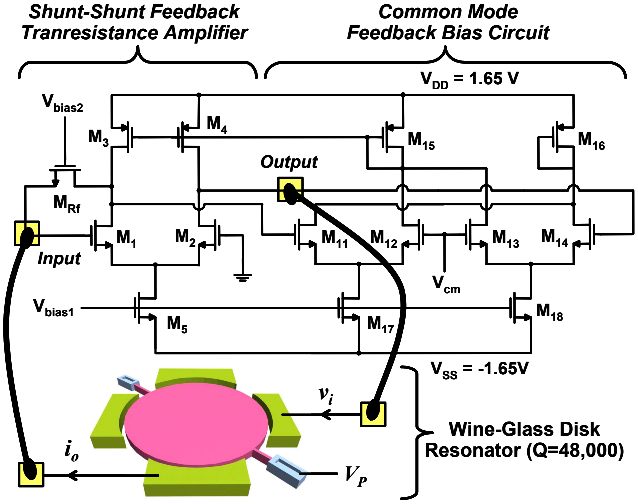

Figure 4.5.5: Circuit schematic of a 61MHz series resonant reference oscillator using a wine-glass disk resonator frequency-setting element with a Q of 48,000 in vacuum, and 10,000 in air.

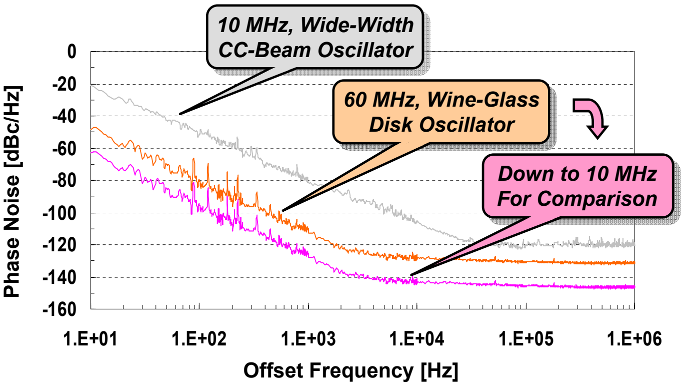

Figure 4.5.6: Measured phase noise density versus carrier offset for the 10MHz CC-beam oscillator of [6] and the 60MHz wine-glass oscillator of Figure 4.5.5, with an extrapolation for the latter down to 10MHz for fair comparison.