A microfabricated atomic clock

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Fabrication techniques usually applied to microelectromechanical systems (MEMS) are used to reduce the size and operating power of the core physics assembly of an atomic clock. With a volume of 9.5 mm^3, a fractional frequency instability of 2.5×10^{-10} at 1 s of integration, and dissipating less than 75 mW of power, the device has the potential to bring atomically precise timing to hand-held, battery-operated devices. In addition, the design and fabrication process allows for wafer-level assembly of the structures, enabling low-cost mass-production of thousands of identical units with the same process sequence, and easy integration with other electronics. © *2004 American Institute of Physics*. [DOI: 10.1063/1.1787942]

Precise time and frequency references provide the critical backbone for a wide range of electronic-based systems such as communication networks, data processing devices, and global positioning. As electronic devices become increasingly mobile and data rates grow, more stringent demands are being placed on the frequency references that synchronize distributed networks, in terms of both stability and flexibility. For more than fifty years, atomic clocks[1,2] have provided the most accurate realizations of both time and frequency. The goal of the present work is to vastly reduce the size and power consumption of an atomic clock to the point where it could be used in a large variety of hand-held, battery-operated instruments such as two-way radios and GPS receivers with much improved tolerance to jamming.[3]

The simplest atomic frequency standards are passive devices based on microwave transitions in a room-temperature vapor of atoms confined in a cell.[4] The smallest physics packages for an atomic frequency reference reported to date[5,6] have a volume of about 1 cm^3 and dissipate several watts of electrical power. In contrast, the most precise type of frequency reference that might be considered generally suitable for portable applications is a temperature-compensated quartz-crystal oscillator. These devices dissipate tens of milliwatts of power and have a fractional frequency instability at 1s of about 10^{-9}, degrading to the 10^{-7} range over longer time periods due to environmental perturbations and aging. This long-term instability makes these devices largely inadequate for applications such as anti-jam GPS.

The physics package we have developed, shown in Fig. 1, draws on microelectromechanical system fabrication techniques[7] to realize small size, low power dissipation, and the possibility for wafer-level integration. At its heart is a Cs vapor cell,[8] fabricated using anodic bonding[9] of borosilicate glass and Si. A square hole of side 0.9 mm was etched into a polished wafer of Si 1 mm thick by use of a KOH etch. Metallic Cs, along with a buffer gas to prevent wall-collision-induced decoherence, was created in the cavity by

reacting a mixture of BaN$_6$ and CsCl in a controlled environment. Two glass wafers bonded on opposite faces of the Si wafer, sealed the Cs and buffer gas inside. The cell was mounted between two planar heater structures made from a film of indium-tin oxide (ITO) deposited on a thin glass substrate. Current was passed through both ITO films to heat the cell to 85 °C, increasing the Cs density correspondingly.

A micro-optics package collimated, attenuated, and polarized the light emitted from a vertical-cavity surface-emitting laser (VCSEL) before it entered the cell. Assembled as shown in Fig. 1, it consisted of a commercially available refractive micro-lens, two neutral density (ND) filters, and a piece of quartz, which served as a quarter-wave plate. A glass spacer unit thermally isolated the rest of the physics package from the baseplate on which the laser was mounted, enabling low-power heating of the cell. The output of the micro-optics assembly was a beam of light ~ 250 μm in diameter with circular polarization and a power of 12 μW. Finally, a Si *PIN* photodiode mounted on a glass substrate detected the light transmitted through the cell. The heaters and photodiode were electrically connected to the baseplate with gold wire-bonds. A longitudinal magnetic field isolated the first-order magnetically insensitive hyperfine clock transition from the magnetically sensitive ones.

The operation of the frequency reference was based on coherent population trapping[10] (CPT), in which two optical fields generate a coherent "dark state" in the atomic hyperfine transition at their difference frequency (Fig. 2). A microwave cavity around the atoms was therefore not required. The VCSEL was tuned to the D2 optical transition in Cs at 852 nm. Laser current modulation at 4.6 GHz was applied from a synthesizer, and the laser frequency stabilized such that the two first-order sidebands on the optical carrier were resonant with the optical transitions from the two components of the hyperfine-split atomic ground state to the $P_{3/2}$ excited state.[11] A CPT-induced reduction of the absorbed light power by 0.91% was observed by sweeping the modulation frequency about the first subharmonic of the 9.2 GHz hyperfine transition. The resonance width of 7.1 kHz was dominated by power broadening from the optical field, although comparable contributions were also present from dif-

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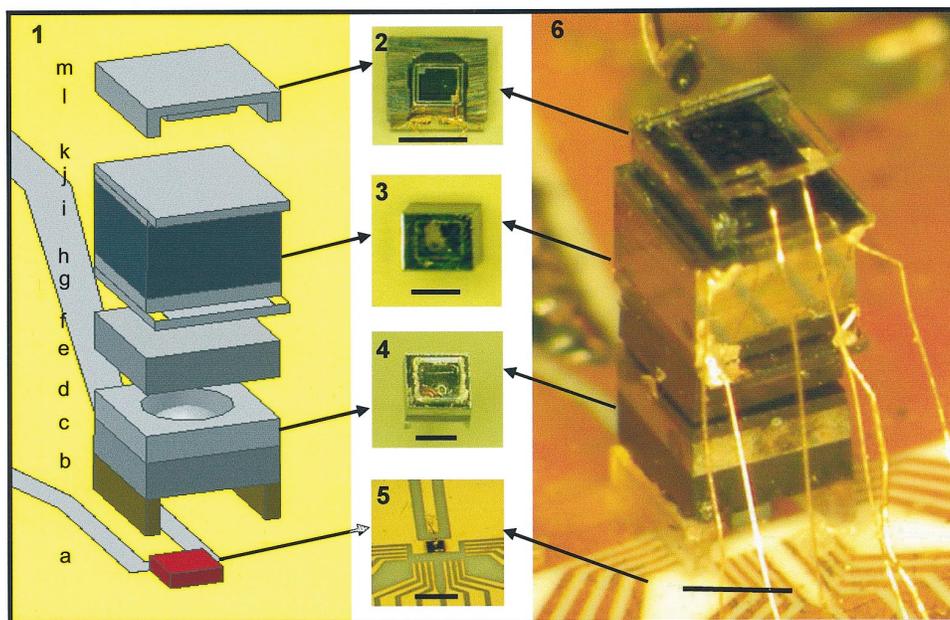[b] Also with: Department of Physics, University of Colorado, Boulder, CO.

FIG. 1. (Color) The microfabricated atomic clock physics package. (1) Schematic of assembly. Layers from bottom to top: (a) VCSEL; (b) glass (500 μm); (c) ND filter (500 μm); (d) spacer/lens (375 μm); (e) quartz (70 μm, not shown); (f) ND filter (500 μm); (g) glass/ITO (125 μm/30 nm); (h) glass(200 μm); (i) Si (1000 μm); (j) glass (200 μm); (k) glass/ITO (125 μm/30 nm); (l) Si (375 μm); (m) glass (125 μm). Total height: 4.2 mm, width and depth: 1.5 mm. Photographs: (2) photodiode assembly, (3) cell assembly, (4) optics assembly, (5) laser assembly, and (6) the full atomic clock physics package realized as a microchip. The black lines in the photographs indicate 1 mm.

fusion of atoms to the cell walls and spin-exchange collisions.[12]

The microwave frequency was locked to the atomic transition by feeding an error signal generated from the CPT resonance back to the tuning port of the synthesizer reference; the stabilized frequency was measured with respect to a more stable, secondary frequency reference. A measure of the resulting fractional frequency fluctuations is shown in Fig. 3. The instability of $2.4 \times 10^{-10}/\sqrt{\tau}$ at short integration times is due to roughly equal contributions from shot-noise on the detected photocurrent, excess AM noise on the laser power, and laser frequency noise converted to intensity noise by the atomic absorption profile. In principle, this instability could be reduced by up to a factor of 10 by exciting the CPT resonance using a laser resonant with the D1 optical transition.[13] The long-term instability is due primarily to a linear fractional frequency drift of about -2×10^{-8}/day. This drift is most likely due to a slow change in the buffer-gas pressure due to residual chemistry within the cell. While this linear drift will need to be addressed eventually, its predict-

able nature nevertheless permits a precise determination of the output frequency even at present. With the linear drift removed, the Allan deviation reaches a minimum of 2.5 $\times 10^{-11}$ at an integration time of 250 s. The remaining long-term instability is consistent with residual fluctuations of the cell temperature, which alter the energy and frequency of collisions of the Cs atoms with the buffer-gas atoms and therefore change the pressure shift.

The electrical power required to run the physics package was 73 mW, and was dominated by the power required to heat the cell above the ambient temperature of 46 °C set by the baseplate. The high baseplate temperature was required to tune the particular laser used in the device to the correct wavelength and is not generally necessary. An advantage obtained through the use of a VCSEL is the extremely low power ($<$5 mW) required to both run the laser and to modulate it with sufficient amplitude to excite the CPT resonance. By modeling the heat flow in the structure, both analytically and with a finite-element computation, the heat loss channels
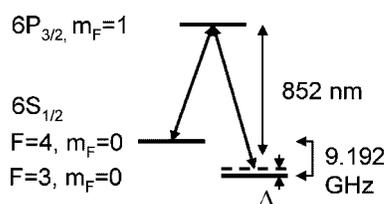

FIG. 2. Excitation of the atomic microwave resonance using coherent population trapping. Two optical fields, produced by modulating the current of a diode laser, are tuned to be simultaneously resonant with transitions from the pair of hyperfine-split ground states to a common excited state. The nonlinear response of the atom generates a resonant excitation of the hyperfine transition at the difference frequency of the optical fields. The resonance is measured by monitoring the transmitted optical power as a function of the modulation frequency detuning from the atomic transition, Δ.
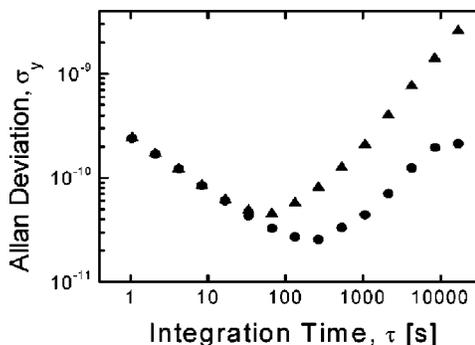

FIG. 3. The frequency-reference fractional frequency instability as a function of integration time, τ, as measured by the Allan deviation. Triangles indicate the instability of the raw frequency output while circles indicate the instability of the device with the linear drift removed.

could be roughly identified. We estimate that 30 mW is lost through the lower spacer unit, and that 24 mW is lost through the six gold wire bonds providing the electrical connections to the baseplate. The remainder is presumably lost through radiation and conduction to the air surrounding the physics package. Modeling of designs incorporating better thermal isolation suggests that the power required to heat the cell could be reduced to below 12 mW without a change in the overall structure.

A key benefit of an atomic clock implemented with the structure shown in Fig. 1 is its amenability to wafer-level fabrication and assembly. Each of the layers that make up the structure, from the laser baseplate to the photodetector mount, could be fabricated as an array of individual components on a large wafer. These wafers could then be bonded together and subsequently diced up into individual atomic-clock physics packages; thousands of physics packages could therefore be fabricated with the same process sequence. This unique fabrication process would reduce the cost of atomic frequency references if implemented commercially on a large scale.

In addition to the physics package discussed here, two other components are required to form a fully functional compact frequency reference. First, a local oscillator capable of generating a signal with frequency 4.6 GHz and sufficient stability to enable it to be locked to the atomic resonance is required. Prime technologies for enabling such a small, low-power oscillator are SiC nano-resonators[14] and thin-film AlN bulk-acoustic-wave resonators (TFRs).[15] Resonators with frequencies above 1 GHz and Q factors over 1000 have been demonstrated and the recent substantial progress in this area provides a valuable synergism with the work described here. Second, miniaturized control electronics are needed to stabilize the cell and laser temperatures and lock the laser wavelength and local-oscillator frequency to their respective atomic transitions. The control systems are not complex and, once the optimum operating conditions are established, could be implemented in a straightforward manner with a small footprint and low power dissipation as an application-specific integrated circuit or in the form of a digital microprocessor.

In conclusion, the atomic clock physics package presented displays an improvement over the previous state-of-the-art by a factor of 100 in volume and a factor of 10 in power dissipation. The device demonstrates convincingly that individual components such as microfabricated alkali vapor cells, micro-optics, and semiconductor lasers can be assembled into a compact structure with an output frequency tied to a highly stable atomic transition. With the addition of control circuitry and a local oscillator, it appears feasible to construct a complete atomic frequency reference with a volume below 1 cm^3, a power dissipation below 30 mW, and a fractional frequency instability below 10^{-11} at 1 h of integration and longer, allowing timing precision at the microsecond level over a day. Furthermore, the integrated design described here could be modified to create millimeter-scale atomic magnetometers as well as a variety of other miniaturized spectroscopic tools and sensors.

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