

● Magnetic Compensation for Second-Order Doppler Shift in LITS

Fractional frequency stability could be the lowest ever achieved.

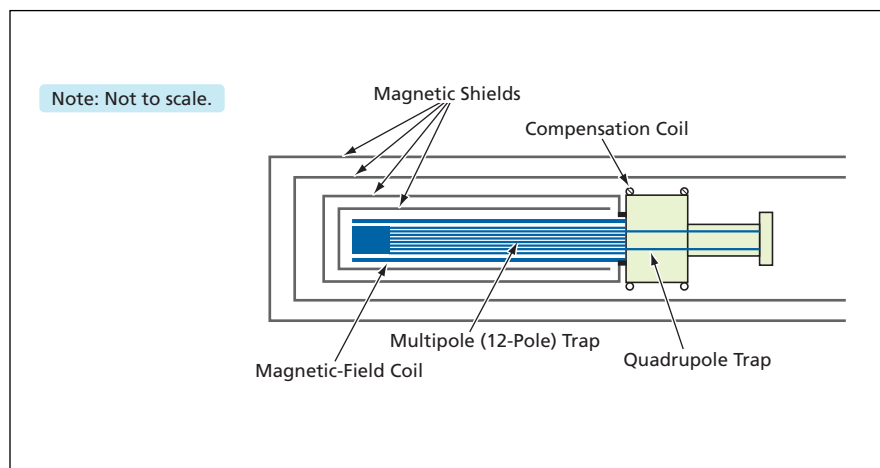
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The uncertainty in the frequency of a linear-ion-trap frequency standard (LITS) can be reduced substantially by use of a very small magnetic inhomogeneity tailored to compensate for the residual second-order Doppler shift. An effect associated with the relativistic time dilatation, one cause of the second-order Doppler shift, is ion motion that is attributable to the trapping radio-frequency (RF) electromagnetic field used to trap ions. The second-order Doppler shift is reduced by using a multi-pole trap; however it is still the largest source of systematic frequency shift in the latest generation of LITSs, which are among the most stable clocks in the world. The present compensation scheme reduces the frequency instability of the affected LITS to about a tenth of its previous value.

The basic principles of prior generation LITSs were discussed in several prior *NASA Tech Briefs* articles. Below are recapitulated only those items of basic information necessary to place the present development in context. A LITS includes a microwave local oscillator, the frequency of which is stabilized by comparison with the frequency of the ground state hyperfine transition of $^{199}\text{Hg}^+$ ions. The comparison involves a combination of optical and microwave excitation and interrogation of the ions in a linear ion trap in the presence of a nominally uniform magnetic field.

In the current version of the LITS, there are two connected traps (see figure): (1) a quadrupole trap wherein the optical excitation and measurement take place and (2) a 12-pole trap (denoted the resonance trap), wherein the microwave interrogation takes place. The ions are initially loaded into the quadrupole trap and are thereafter shuttled between the two traps. Shuttling ions into the resonance trap allows sensitive microwave interrogation to take place well away from loading interference. The axial magnetic field for the resonance trap is generated by an electric current in a finely wound wire coil surrounded by magnetic shields.

In the quadrupole and 12-pole traps, the potentials are produced by RF voltages applied to even numbers (4 and 12, respectively) of parallel rods equally spaced around a circle. The polarity of the voltage on each rod is opposite that



A Typical Latest-Generation Multipole LITS contains a quadrupole trap and another multipole (e.g., 12-pole) trap surrounded by a coil that generates a nominally uniform axial magnetic field. In the present compensation scheme, a controlled magnetic inhomogeneity is introduced by use of a compensation coil.

of the voltage on the adjacent rod. As a result, the amplitude of the RF trapping field is zero along the centerline and increases, with radius, to a maximum value near the rods.

As the number of ions temporally varies in a small range about a target value, space-charge repulsion causes the ensemble of ions to occupy a varying volume within the trap. The change in radial occupation results in a change in the time-averaged magnitude of the trapping RF field sampled by the ions and a change in ion micromotion amplitude, which will cause a corresponding change in the second-order Doppler shift. (The first-order Doppler shift is eliminated by the geometry of the trap and the polarization of interrogating microwave field.)

In a 12-pole trap, the ions are free particles for most of their trajectories, interacting with significant RF amplitude only at the edges of the trap. As a result, the time-averaged RF amplitude sampled by the ions is significantly smaller, for the same number of ions trapped, than it is in a typical quadrupole trap used in an earlier-generation LITS. The sensitivity to the second-order Doppler shift is more than 10 times smaller than in the case of a quadrupole-trap LITS, making the long-term stability of a 12-pole-trap LITS comparable to or even better than that of the best hydrogen masers. Nevertheless, the second-order Doppler shift remains the largest shift in the LITS, and the

problem is to reduce it even further.

As a solution to this problem, the present compensation scheme exploits the following facts:

- The ion-number-dependent second-order Doppler shift is negative and increases in magnitude as the number of ions increases.
- Heretofore, in designing a LITS, great care has been taken to provide a uniform magnetic field within the trap so that as the volume occupied by the ions changes, the average magnetic field sampled by the ions does not change.
- Notwithstanding the nominal uniformity of the magnetic field as described above, it is possible to introduce a well-controlled magnetic-field inhomogeneity, such that ions in a changing occupation volume sample a slightly different magnetic field. The resulting inhomogeneity in the second-order Zeeman shift can be used to counteract the second-order Doppler shift.

Accordingly, in the present compensation scheme, one or more coaxial compensation coil(s) is or are used to generate one or more small magnetic-field inhomogeneities. The placement of, and currents in, the coils can be chosen to obtain either a positive or negative change in the second-order Zeeman shift with a change in the number of ions. By careful adjustment of the current(s) in the compensation coil(s), the

second order Zeeman shift can be made to almost exactly cancel the residual second-order Doppler shift.

In an experimental implementation of this scheme, a 5-turn compensation coil was placed between the quadrupole and 12-pole traps and was excited

with a current of 3 mA. With this compensation scheme, the measured fractional frequency stability of the second-order Doppler shift is 3×10^{-17} . As a result, all systematics in the clock, and the clock itself, should have a long-term stability of better than 5×10^{-17} ,

which would be the best ever measured in any clock.

This work was done by Eric Burt and Robert Tjoelker of Caltech for NASA's Jet Propulsion Laboratory. For more information, contact iaoffice@jpl.nasa.gov NPO-43199

Nanostructures Exploit Hybrid-Polariton Resonances

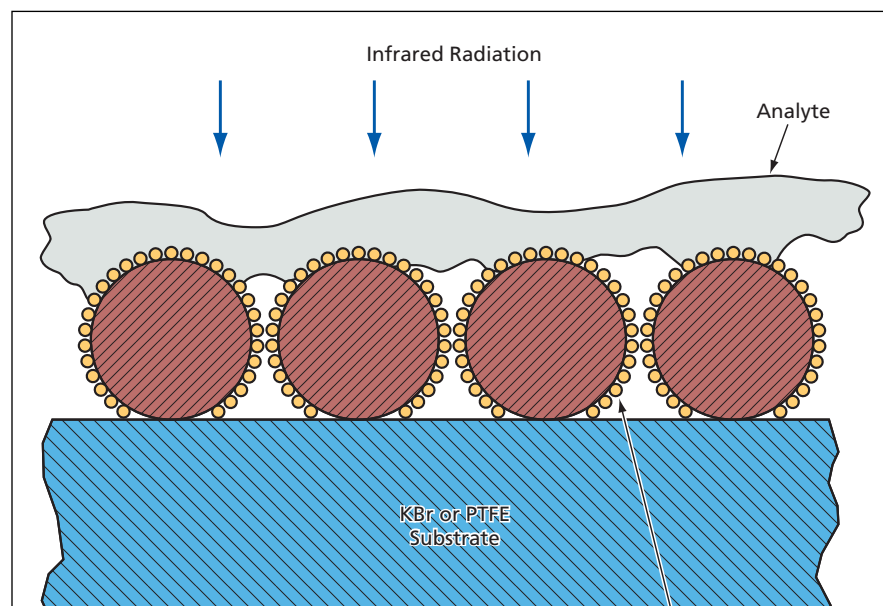
Infrared absorption or scattering by molecules of interest can be greatly enhanced.

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Nanostructured devices that exploit the hybrid-polariton resonances arising from coupling among photons, phonons, and plasmons are subjects of research directed toward the development of infrared-spectroscopic sensors for measuring extremely small quantities of molecules of interest. The spectroscopic techniques in question are surface enhanced Raman scattering (SERS) and surface enhanced infrared absorption (SEIRA). An important intermediate goal of this research is to increase the sensitivity achievable by these techniques. The basic idea of the approach being followed in this research is to engineer nanostructured devices and thereby engineer their hybrid-polariton resonances to concentrate infrared radiation incident upon their surfaces in such a manner as to increase the absorption of the radiation for SEIRA and measure the frequency shifts of surface vibrational modes.

The underlying hybrid-polariton-resonance concept is best described by reference to experimental devices that have been built and tested to demonstrate the concept. The nanostructure of each such device includes a matrix of silicon carbide particles of approximately 1 micron in diameter that are supported on a potassium bromide (KBr) or poly(tetrafluoroethylene) [PTFE] window. These grains are sputter-coated with gold grains of 40-nm size (see figure).

From the perspective of classical electrodynamics, in this nanostructure, that includes a particulate or otherwise rough surface, the electric-field portion of an incident electromagnetic field becomes concentrated on the particles when optical resonance conditions are met. Going beyond the perspective of classical electrodynamics, it can be seen that when the resonance frequencies of surface phonons and surface plasmons overlap, the coupling of the resonances



Circumferential Belts were formed by diamond turning on the initially cylindrical surface of a CaF₂ rod. The radial depths and axial widths of the belts were chosen to make some of the belts act as single-mode and some as multi-mode WGM resonators.

gives rise to an enhanced radiation-absorption or -scattering mechanism.

The sizes, shapes, and aggregation of the particles determine the frequencies of the resonances. Hence, the task of designing a nanostructure to exhibit the desired radiation-absorption properties translates, in large part, to selecting particle sizes and shapes to obtain the desired enhanced coupling of energy from photons to plasmons and phonons. To broaden the spectral region(s) of enhanced absorption, one would select a distribution of particle sizes and shapes.

In a test, the infrared spectra of one of the experimental nanostructures described above were measured before and after the nanostructure was coated with an approximately-monomolecular-thickness layer of poly(methyl methacrylate) [PMMA]. Among other things, the measurements showed that in the af-

fected wavelength range, in the presence of the nanostructure, the magnitude of absorption by the thin PMMA film was comparable to the absorption by a considerably thicker PMMA film without the nanostructure.

This work was done by Mark Anderson of Caltech for NASA's Jet Propulsion Laboratory.

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