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AN IMPROVED, OPTICALLY PUMPED, PRIMARY FREQUENCY STANDARD: JOINT DEVELOPMENT BY CRL and NIST

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Abstract

An improved primary frequency standard based on an optically-pumped, thermal, atomic beam has been jointly developed by CRL and NIST. The design details are presented along with the preliminary evaluation results. The standard will be evaluated both in the US and Japan.

Introduction

The Communications Research Laboratory (CRL) of Japan and the National Institute of Standards and Technology (NIST) of the US have collaborated on the development of an improved primary frequency standard based on an optically pumped, thermal atomic beam. The goal of this development has been a primary standard with uncertainty limits at least equal to that of the existing NIST standard but with a more totally engineered system capable of nearly automated evaluations. Additionally, the standard will be fully evaluated both at the Boulder laboratories of NIST and at the Tokyo laboratories of CRL. This will be the first evaluation of a high-performance, primary frequency standard in two different environments.

Physical System

The atomic-beam tube is functionally equivalent to that of the previously developed device known as NIST-7 [1]. The Ramsey microwave cavity is 1.55 m long and is terminated in De Marchi rings [2]. The C-field is generated by a shielded solenoid that extends over the entire length of the machine, including the optical state preparation and detection regions.

The diode laser system is based on a multi-electrode, distributed-Bragg-reflector (DBR) technology. This monolithic device is vastly less environmentally sensitive than the extended cavity diode-laser systems that have been used on NIST-7. The laser is frequency stabilized by an RF sideband technique [3] to a saturated absorption feature in an external, evacuated cesium cell. The multi-electrode nature of the laser allows the RF modulation to be added directly to the laser without causing AM, which would bias the resulting lock point. This combination of the monolithic laser and RF sideband modulation scheme results in a laser system that is extremely robust, remaining locked indefinitely. Separate optical frequencies for optical state preparation and detection are derived from this laser using an acousto-optic modulator.

The computer-controlled master operating system is written in C++ and uses object-oriented programing. This provides an extremely powerful and flexible platform that can be easily reconfigured as the specific hardware and/or needs of the controlling functions change. This clock operating system performs the function of the main frequency-control servo using a slow square-wave modulation with blanking intervals following a frequency switch. Additionally it evaluates and controls most of the significant terms in the error budget as well as recording and archiving all the data. It periodically monitors the Zeeman frequency and controls it by feedback to the C-field current, thus increasing the effective magnetic shielding by the gain of the servo system. It also monitors and controls the microwave power, thus stabilizing the second-order Doppler shift. During an evaluation cycle, this system (1) analyzes the velocity of the atomic beam by recording the Ramsey signal at several different microwave powers[5], (2) analyzes cavity pulling, the effect of magnetic field inhomogeneity and Rabi line overlap shifts by recording the offset between each Ramsey line and its corresponding Rabi pedestal across the entire Zeeman spectrum[6], (3) looks with a sensitivity of a few parts in 10^{15} for any bias term that has dependence on microwave power and (4) with similar sensitivity, looks for any bias terms that result from an extraneous signal synchronous with the modulation.

The RF synthesis is of a type that was previously developed at NIST [4]. It is capable of supporting a standard with short-term stability $\sigma_y(\tau)<10^{-13}\,\tau^{-1/2}$ and long-term stability $\sigma_y\,(\tau)<10^{-17}$. In this system, a high-quality reference oscillator is multiplied up to 500 MHz, where an adjustable offset of nominally 10.701 MHz from a direct digital synthesizer (DDS) is added. The resulting 510 MHz signal is then filtered, amplified and applied to a step recovery diode. The 18th harmonic generated in this process is then resonant with the cesium transition. The system can lock the quartz local oscillator (LO) to the atomic resonance as in a normal, stand-alone atomic clock. However, we usually phase lock the LO to the "house maser". In this case, the output of the standard is the recorded list of numbers sent to the DDS as the servo steers it to the atomic resonance.

The carefully synthesized RF radiation passes through a power-control servo system on its way to the atomic-beam tube. This system is necessary to give the computer the flexibility both to perform automated evaluations as well as to control small, environmentally driven power variations that can effect the second-order Doppler shift. Functionally, this is just a PIN attenuator followed by a power amplifier and a resistive power divider. A highly stable power meter on one output of the power divider provides the signal for the computer control of the PIN attenuator. The power meter is calibrated automatically and periodically by reference to the atomic clock signal itself. Additionally, there are a number of test points built into this system that allow continuous monitoring of charateristics like spectral purity and synchronous AM.

The design of this unit is complicated because it must not degrade the spectral purity and phase stability so carefully prepared in the synthesizer. Also, it must not write any AM on the RF that is synchronous with the modulation cycle. And, it must not radiate any RF into the lab that could find unintended ways into the atomic-beam tube and lead to transition probability with uncontrolled phase. All DC power and low frequency signals are coupled into and out of this box through quarter-wave stub-tuned filters that trap the 9 GHz radiation. The computer signals are optically coupled into a micro controller inside the box. This micro controller generates signals for latching DAC's that actually drive the attenuator. In this way, the box is maintained RF tight and there are no switching transients during a clock data-taking cycle that could contaminate the RF spectrum.

Program Status and Results

As of this writing (May 1998) the atomic-beam tube, laser system and RF synthesis chain are finished and under evaluation. The final computer code and completed evaluation in NIST's Boulder labs remain works in progress. When completed, the entire system will be relocated to the CRL laboratories in Tokyo and the evaluation process repeated.

The relevant atomic physics as well as aspects of the atomic beam tube related to accuracy have been evaluated. The results are presented in Table 1. No summation of errors or "total combined uncertainty" number is given because contributions from the electronics are not included here. The evaluation of some of these items must await the operation of the final system components.

Table 1. Evaluated systematic effects.

PHYSICAL EFFECT	Bias $y\cdot10^{15}$	Uncertainty $y\cdot10^{15}$
Atomic Velocity and Second-Order Doppler	**≈300**	**0.1% 1**
Second-Order Zeeman	**$\approx10^5$**	**0.1**
Cavity pulling	**1**	**0.1**
Rabi pulling	**0**	**0.01**
Cavity phase (E-t-E)	**≈250**	**3**
Cavity phase (distributed)	**0**	**1**

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