Microwave Leakage as a Source of Frequency Error and Long-Term Instability in Cesium Atomic-Beam Frequency Standards

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Abstract

We identify leakage from the microwave electronics in cesium atomic-beam frequency standards as a potential source of frequency error and instability in these standards. The problem arises when radiation that is phase coherent with the interrogating radiation finds its way to the atoms in regions outside the Ramsey cavity. We discuss techniques for evaluating and reducing the problem.

Introduction

Reduced to its most basic elements, an atomic clock is an electronic oscillator locked to an atomic resonance. In the case of cesium atomic-beam standards, the atoms are moving at thermal velocities, and the resonance is in the microwave region at 9.192 GHz. The atom motion could cause a first-order Doppler shift as great as a part in 10^6 if the interrogating radiation were counter- or co-propagating with the atomic beam. To obtain frequency accuracy or stability of a part in 10^{14}, this effect must be controlled to a part in 10^8. It is this extremely high sensitivity to the motion of the atoms that creates the sensitivity to microwave leakage.

The principal purpose of the microwave cavity is to provide the necessary control over the first-order Doppler effect. Inside the cavity, the microwave power flow in the direction of the atomic beam has been greatly reduced relative to that of a freely traveling wave. The remaining effects are interpreted as end-to-end and distributed-cavity phase shift[1]. In commercial standards, these residual effects are assumed to be small. In primary standards where accuracy is a consideration, these effects are measured. In either case, any frequency shift is assumed to be stable.

However, if radiation finds its way from the microwave generator to the atoms while they are outside the microwave cavity, the required control over the first-order Doppler shift may be lost. Only radiation that is phase coherent (i.e., radiation from the microwave generator operating the device in question) causes the most serious problems. Radiation that is nearly the same frequency (e.g., from a nearby clock) can also induce undesirable transition probability and, hence, frequency shifts. But the relative phase evolution should cause the shifts to average out. Phase coherent radiation, on the other hand, can cause a static frequency shift.

This is because it has different phase than the radiation in the cavity. The moving atoms see this spatial phase variation as a time varying phase, hence, a frequency shift. This is classical end-to-end phase shift and would be accounted for in a beam reversal evaluation if it is stable over the time of the evaluation[1]. However, frequency shifts caused in this way are often unstable because the leakage radiation travels over uncontrolled paths and arrives with uncontrolled phase. Changes in the paths cause changes in the phase and hence, changes in the frequency of the standard.

We have developed a theoretical model for the frequency shift caused by radiation outside the microwave cavity. The result includes power- and modulation-dependent factors multiplied by a spatial integral of the component of the leakage field in quadrature with the interrogating radiation, all averaged over atomic velocity. Since the spatial dependence of the leakage radiation is not known, only qualitative results have been obtained. Because the shift is linear in the radiation amplitude, leakage radiation that is 120 dB weaker than the interrogating radiation inside the microwave cavity can cause a significant frequency shift (parts in 10^{14}).

However, we do not need a quantitative model to deal with the problem. The fact that this effect is not widely recognized indicates that it is usually small. Most systems need only a little additional isolation to reduce the effect to acceptable limits. To achieve the desired isolation two areas should be investigated: leakage from the microwave electronics outside the beam tube and avenues by which the radiation gets into the beam tube.

Microwave leakage

All microwave equipment leaks at some level. Systems that have been assembled without special attention to this fact may leak orders of magnitude more than those that have been assembled with care. The flanges in X-band waveguides may leak badly if they are not extremely flat and/or located at nodes in standing-wave systems. Cavity-tuning screws are a special problem. Replacing waveguide structures with coaxial technology using the common SMA connectors is not better. SMA connectors require precise torque to achieve adequate shielding. Furthermore, many SMA-connectorized components (attenuators, circulators, isolators, directional couplers, couplers, etc.) are extremely leaky. Many of them actually have an epoxy-filled hole all the way through from the outer conductor to the inner conductor to hold them together. Solutions involve carefully selected components, rf gaskets, metal filled epoxy, and absorbing material placed over the leaking component.

Building a microwave leak detector and inspecting a system for leaks is relatively simple. We use a simple antenna, either a magnetic field loop or an electric field dipole, followed by a heterodyne receiver; Fig. 1. The microwave generator from a second set of clock electronics makes a good local oscillator (LO). Alternately, a microwave signal generator tuned near the cesium resonance works.

With the heterodyne beat signal thus translated to the audio region, an FFT spectrum analyzer is sensitive enough to detect most troubling radiation. Interchanging the LO and the device under test allows all of the equipment to be checked for leaks.

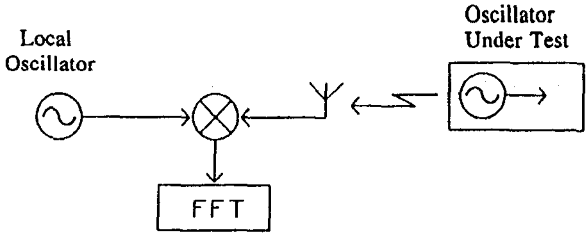

Fig. 1 Heterodyne detector used for rf leak detection.

The atomic beam tube

The mechanisms by which the radiation gets into the atomic beam tube are as important as the sources of radiation leakage. To find these paths, we split off some of the power from the microwave generator and applied it to a microwave horn. When this is directed at unprotected parts of the beam tube, large frequency shifts can be induced. One can then scale from the power radiated from the horn to the power leaked by the microwave plumbing to infer the size of the problem. We found that essentially all of the radiation is coupling into the beam tube through unfiltered, DC or low frequency feedthroughs such as C-field, Zeeman coils or degaussing leads. Unused pins on electrical feedthrough headers are often about $\lambda/4$ long and make effective antennas. Ferrite beads located right at the vacuum seal are effective filters. We have also used microwave-absorbing foam to shield unused pins.

Results

We have applied these techniques to NIST-7, the US primary frequency standard. Before the problem was identified and solved we had unexplained frequency shifts of several parts in 10^{14}. Once the problem was identified, we were able to force the frequency shifts by changing the phase delay between the microwave generator and the beam tube. Figure 2 shows a series of frequency measurements relative to a hydrogen maser where we systematically changed the phase delay between every measurement. The first four measurements were made before we closed the leaks, while the last four were made after. The improvement indicated by these measurements is at least 10 dB and is limited by the statistical validity of the measurements. Our electrical measurements on the leaks indicate that we made an improvement of at least 50 dB.

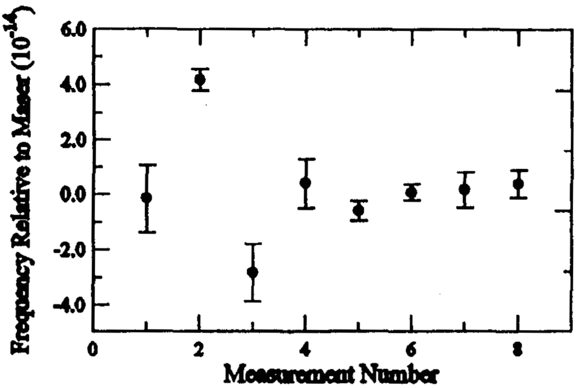

Fig. 2 Variation in the frequency offset measured between NIST-7 and a hydrogen maser while the phase delay from the microwave generator to the beam tube was systematically changed. The first four points are with leakage fields while the last four are after the leakage fields were reduced by the techniques outlined here.

Conclusion

Radiation leakage from the microwave electronics in a cesium atomic-beam frequency standard that finds its way into the beam tube can cause substantial frequency shifts. These shifts may be unstable with time because they are dependant on the phase of the radiation which arrives at the atoms via uncontrolled pathways. The effect may lead to frequency errors in primary standards and to long-term instability in commercial standards. The fact that this effect has gone largely unrecognized suggests that it is usually small. Hence, small improvements in the leakage from the microwave electronics and attention to the pathways by which this radiation enters the beam tube are sufficient to reduce the problem to acceptable levels.

References

1. Jacques Vanier and Claude Audoin, The Quantum Physics of Atomic Frequency Standards, Adam Hilger 1989, Section 5.6.4(A).