# Microwave leakage shift suppression based on home made DDS

Pingwei Lin, Shi Liu, Nianfeng Liu
National Institute of Metrology (NIM), Beijing, China

**Abstract:** A home made DDS based on a FPGA and a DAC was designed to suppress microwave leakage shifts. The phase invariability was realized utilizing the DDS. The spectrum performance and phase noise of the DDS were measured and were good enough to be used for the microwave synthesizer. From the experiment result of fountain clock the introduced frequency shift by switch DDS output frequency should be less than 2E-16.

## I. Introduction

Microwave leakage sometimes can cause several E-15 or even larger frequency shifts in fountain clocks and is difficult to be evaluated. The careful mechanical design and manufacture of fountain clocks, especially the careful design and manufacture of the microwave cavity and the cut-off waveguides, reduces the microwave leakage frequency shift, but still can not eliminate it completely.

In order to suppress the microwave leakage shift, a microwave synthesizer using a Mach-Zehnder interferometer switch for the RF signal was first manufactured and used in a LNE-SYRTE fountain clock[1]. As most microwave mixers show considerable phase transients when the input signal power is changed, a sub-micro radian resolution Triggered Phase Transient Analyzer (TPTA) used to test such possible phase transients is necessary [1]. It is not so easy for most laboratories to build such TPTA.

If we could change the frequency of the direct digital synthesis (DDS) output signal without changing the phase when the frequency is changed back, we could reduce the frequency shift of microwave leakage considerably.

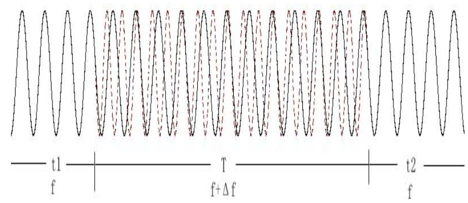


Figure 1: Before time t1, the signal frequency is f (black solid curve at the left); From time t1 to t1+T, the signal frequency is f+ Δf (red dot curve in the middle); After time t1+T, the signal frequency is f (black solid curve at the right). Δf*T is integer.

The phase of the signal can be written as: Phase1= $2\pi f*T+\Phi$. Here f is the signal frequency, $\Phi$ is the initial phase of the signal, T is the time. If we change the signal frequency from f to f+ Δf, then the phase of the signal can be written as: Phase2= $2\pi(f+\Delta f)*T+\Phi = 2\pi f*T+\Phi+2\pi\Delta f*T$.

When the signal phase changes $2\pi *n$ (n is an integer), the actual signal phase has no change. In Figure 1, the signal frequency is changed to f+Δf from time t1 to t1+T, but the phase of the signal after time t1+T shows no change when Δf*T is integer, as if the signal frequency is always f. Such phase invariability DDS will help to reduce microwave leakage shifts significantly.

Unfortunately commercial DDS, such as AD9852 and AD9956, show large frequency change delays when the external FM signal changes from 0 to 1 or from 1 to 0, and the delay time is not fixed. So the actual time, during which the frequency is f+Δf, is not exactly T as desired. This could cause hundreds of micro-radian phase change, and a corresponding about E-14 frequency bias in a fountain clock.

## II. Structure of home made DDS

In order to circumvent the problem due to commercial DDS, a home made DDS, based on a Field Programmable Gate Array (FPGA) and a 14-bit high speed Digital to Analog Converter (DAC), was constructed. Two 48-bit frequency tuning words, one 48-bit phase accumulator and a sine wave look up table were constructed in a FPGA. The sine wave look up table had 14-bit amplitude resolution and 14-bit address resolution. The final 14-bit digital outputs of the FPGA were passed to the DAC stage to synthesize a sine waveform. The FPGA and DAC were driven by an external 100MHz clock signal. A commercial 10.7 MHz low-pass filter was used to filter the high frequency signal after DAC. Unlike in commercial DDS, the delay time of change from one frequency tuning word to another in such a DDS was less then half a clock period. So we could control the duration T of the output frequency f+Δf precisely.

A D-type latch was also constructed in FPGA. The clock frequency of the D-type latch was set to 100 MHz /$2^{13}$. The external frequency modulation (FM) signal was first passed to the input pin of the D-type latch, then it was latched by the D-type latch. So the pulse width of the output FM signal from the D-type latch was always n* $2^{13}$/(100MHz) (n is an integer). When Δ f was set to m*100MHz/$2^{13}$ (m is an integer, about 12.2 kHz when m=1), Δ f*T= m*100MHz/$2^{13}$ * n* $2^{13}$/(100MHz) =m* n. Δf*T was an integer in any situation, so phase invariability was guaranteed.

A single-chip Microcomputer (MCU) was used to set the frequency tuning words of the FPGA through interface lines. The MCU also could communicate with a PC through RS232 and get frequency tuning word data from a PC program.

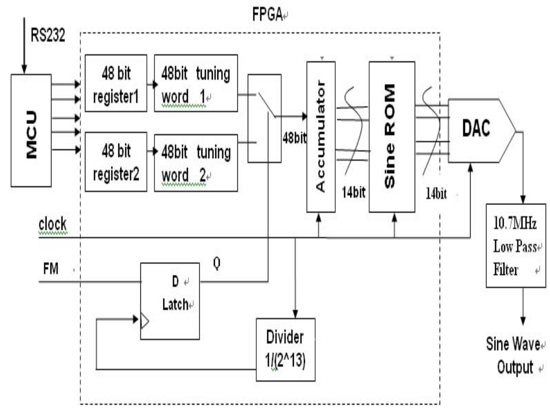


Figure 2: Structure of home made DDS

## III. DDS performance test

In order to testify that the phase invariability was realized in our DDS, two 5MHz sine waves were displayed on an oscilloscope simultaneously. One 5MHz sine wave was the output of the DDS, another was from a frequency synthesizer. The frequency synthesizer and the DDS had the same time base. So there was no phase change between two 5MHz sine waves in the longterm. The 5MHz sine wave from the DDS was changed to 5MHz+100MHz/8192 (about 5.0122MHz) in 0.8192 ms (m=1, n=10), then it was changed back to the 5MHz sine wave again. When these two 5MHz sine waves were compared again, no phase change was found. After many (even more than one million) switches between 5MHz and 5MHz+100MHz/8192, still no phase change was observed. The phase invariability was testified in our DDS.

In order to test the near side spectrum performance of our home made DDS, the output sine wave signal from our DDS was mixed with a signal from a commercial synthesizer which had a very good spectrum performance. The mixed 50kHz signal was connected to a FFT spectrum analyzer. The near 50Hz spurs were better than 60dB. Other spurs from 1Hz to 1kHz were better than 70dB. The near side spectrum performance of a commercial DDS AD9956 was also tested in the same environment. Tests showed that the near side spectrum performance of our home made DDS was as good as the one of the commercial DDS. From spectrum measurement data, the phase noise of the DDS was estimated and was good enough to be used in the microwave synthesizer. In order to get the accurate phase noise of the DDS, the phase noise of the DDS was measured by a commercial phase noise measurement instrument and reached -105 dBc/Hz @1Hz, -117dBc/Hz @10Hz and -125dBc/Hz @100Hz, much better than the previous estimation.

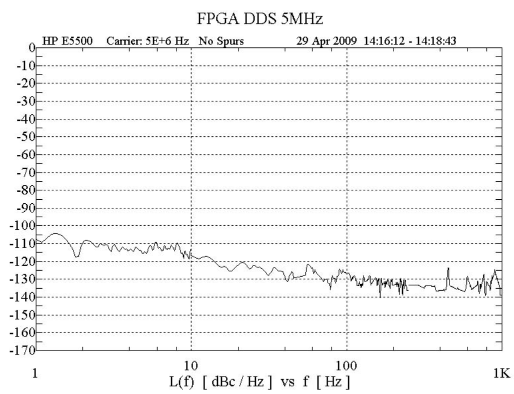

Figure3: Phase Noise of home made DDS

## IV. Test in fountain clock

A SSB mixer was used in our microwave synthesizer. The 9.2GHz microwave signal is mixed with the 7.368MHz signal to generate the 9.192GHz clock transition microwave signal. The commercial frequency synthesizer DS345 was replaced by our home made DDS to generate the 7.368MHz signal in the cesium microwave synthesizer. The stability of the NIM5 fountain clock was about 2E-13 $\tau^{-1/2}$ ($\tau$<5000s). When this cesium microwave synthesizer was used in the NIM5 fountain clock [2], no frequency stability degradation was observed.

The servocontrol program of the NIM5 fountain clock could servo the frequency in one condition for a short time and servo the frequency in another condition for a short time automatically. This alternate frequency servo in two conditions could eliminate frequency drifts of the H-maser. So the frequency difference between two sets of servo data is just caused by the different conditions.

In order to check the phase invariability again by cesium atoms, two different conditions were set. One condition was no microwave frequency change during the whole Ramsey interrogation period. Another condition was that the microwave frequency was 12.2kHz higher or lower when cesium atoms were outside the microwave cavity. The day stability of the NIM5 clock was about 2E-15. The average frequency difference of four days servo data in the two conditions was less than 1E-15. This experimental result shows that the microwave leakage should be small in our NIM5 clock and the phase invariability of our home made DDS should be true, though there still exists the possibility that the microwave leakage frequency shift is exactly the same as the shift caused by the DDS phase change.

Although the phase invariability is guaranteed in the digital part of our home made DDS, we are still not sure that the different frequency sine wave in several millisecond ago could cause the sine wave small phase shift in analog part of our DDS or not. But we are sure that the sine wave phase shifts caused by higher frequency sine wave and lower frequency sine wave are in different direction and these two shifts should be almost symmetric.

In order to check the possible small phase shift, two different conditions were set. One condition was that the microwave frequency was 12.2kHz higher when cesium atoms were outside the microwave cavity. Another condition was that the microwave frequency was 12.2kHz lower when cesium atoms were outside the microwave cavity. The average frequency difference of 8 days servo data in the two conditions was less than 1.2E-15. This experiment result showed that no evident frequency difference existed within the frequency resolution limited by the frequency stability of the NIM5 fountain clock. Even if the average frequency difference in the two conditions was regarded as 1.2E-15, as such frequency shifts had different sign and almost the same amplitude, the average of all frequency servo data in the two conditions could cancel most parts of such a possible frequency shift. So the frequency shift caused by switching the DDS output frequency should be much less than 2E-16.

## V. Conclusion

The phase invariability was realized in our home made DDS based on a FPGA and a DAC. The spectrum performance and phase noise of the DDS were measured and were good enough to be used in the microwave synthesizer. By setting the microwave frequency at the Ramsey center frequency when cesium atoms are inside the microwave cavity, and setting the microwave frequency several ten kilohertz higher than the Ramsey center frequency in some servo periods and several ten kilohertz lower than the Ramsey center frequency in other servo periods when cesium atoms are outside the microwave cavity, the most part of microwave leakage shift is suppressed and a possible frequency shift introduced by switching the DDS output frequency is cancelled at the same time. The introduced frequency shift should be less than 2E-16.

## Acknowledgments

The authors thank Dr. S. R. Jefferts of NIST for his very useful discussion. The authors thank Dr. S. Weyers of PTB for the correction of this manuscript. The authors also thank Dr. Tianchu Li of NIM for his support of this research work.

## References

[1] G. Santarelli, G. Governatori, M. Lours,et al, Phase Transient Measurement at the Micro radian level for Atomic Fountain Clocks, Proceedings of the 20th EFTF, 2006.

[2] LI Tian-Chu, LIN Ping-Wei, LI Ming-Shou, et al, The Transportable Cesium Fountain Clock NIM5:Its Construction And Performance, SFSM 2008.