A New 9-GHz Synthesis Chain for Atomic Fountain Clocks

A. Sen Gupta
National Physical Laboratory
Dr K S Krishnan Road
New Delhi, INDIA
sengupta@mail.nplindia.ernet.in

R. Schröder, S. Weyers and R. Wynands
Physikalisch-Technische Bundesanstalt
Bundesallee 100
38116 Braunschweig, Germany

Abstract— **We describe a new microwave synthesizer chain to produce the 9.192 GHz Cs frequency currently being developed in a cooperation of PTB and NPL India. In this synthesis a 9600GHz YIG oscillator is locked to a 5 MHz quartz oscillator via a divider chain (9600 : 8 : 3 : 4 : 20). Along the way, a signal of 407.37 MHz is generated with the help of direct digital synthesis (DDS). The required interrogation frequency is obtained by mixing (9600 MHz - 407.37 MHz = 9192.63 MHz). The signal from the atoms is then used to steer the 5 MHz quartz frequency. We discuss the preliminary results of studies of the metrological features – namely, the spectral purity, phase noise and the long term phase stability - of the few prototype units constructed so far.**

I. INTRODUCTION

Currently the 9-GHz synthesis chain for PTB's fountain clock CSF1 uses a design developed for thermal-beam caesium clocks long time ago [1]. However, with fountain clocks now working below 10^{-15} relative uncertainty and instability a synthesis chain with better performance is needed [2-5]. In particular, this concerns the long-term instability, with a design goal of 10^{-17}/day. Another goal of the present effort is to replace the commercial synthesizer in the synthesis chain by a Direct Digital Synthesizer (DDS) chip. The inclusion of a DDS chip in the design has a number of advantages over the existing synthesis chain. Modulation of frequency and phase can be performed by the computer-controlled DDS chip in the course of the 407.37 MHz signal synthesis. It would therefore be relatively easy to switch from square-wave frequency modulation to phase modulation in the interrogation cycle. Furthermore, when the new chain is connected to the state selection cavity it will be possible to choose the appropriate detuning and waveforms for the rapid-adiabatic passage method of controlling the cold-collision shift [6].

II. DESIGN OVERVIEW

The present design is very similar in its basic philosophy with the space clock synthesizer design earlier [3]. At the heart of this synthesizer is a frequency divider chain that divides a 9.6 GHz YIG oscillator output to 5 MHz. Commercially available low noise digital dividers have been used for this purpose and have been found to be adequately compact, stable and provide long term reliability of operation. There are no multipliers or narrow-band filters in the synthesis chain. The 5 MHz output of the divider is phase compared with the output of a low noise 5 MHz OCXO and the error used to phase lock the 9.6 GHz YIG. Along the divider chain a 400 MHz signal is taken out. This is mixed with a 7.368…MHz signal in an upper-sideband (USB) mixer to produce a 407.368…MHz, which is then further mixed with the 9.6 GHz to produce the required Cs output at 9.192... MHz. The 7.368…MHz is produced by a commercially available 48-bit DDS chip, which is clocked by 50 MHz obtained by frequency dividing the 400 MHz. The output of the DDS is controlled by a 8-bit microcontroller.

The microcontroller has several resident operating programmes – such as Ramsey fringes scan, Square wave frequency modulation, Square wave phase modulation, Zeeman frequency scan etc. The programming mode and the respective input parameters are input to the microcontroller from the central computer over a serial port. The user outputs of the synthesizer are: 5 MHz and 100 MHz sine waves both obtained via isolation amplifiers. The synthesizer output can be steered by voltage control of the 5 MHz oscillator using a DC error signal derived from the physics package of the Cs fountain. There is also the possibility of phase locking the output to a 5/100 MHz output of a H-maser or other high stability reference. The synthesizer design is also suited for the inclusion of a microwave source of superior short-term stability in the future, for instance a cryogenic sapphire oscillator, which is chosen to have a frequency within a few tens of MHz of the sub-harmonic multiples of 9.6 GHz. In this case the 9.6 GHz YIG could be phase locked to this external reference using an additional DDS to bridge the difference in frequency.

III. MEASUREMENT RESULTS

The metrological features of the synthesizers are best characterized by studies of the three main aspects – spectral purity, phase noise and the stability of the phase variation through the synthesis chain. In the following we describe the results of our studies of the above aspects based on the few prototypes constructed so far.

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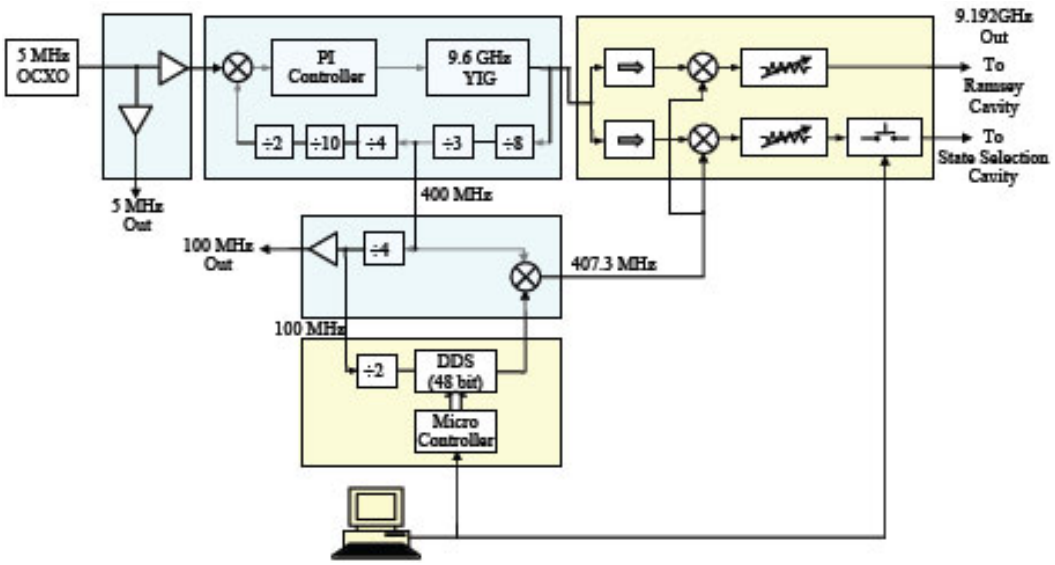

Figure 1. Concept and functional blocks of the synthesizer.

A. Spectral Purity

The spectra of the 9.192 GHz output of the synthesizer are shown in Fig.2. Over the frequency range ± 50 kHz about the carrier there are no visible spurs above the noise pedestal in shape of a broad peak at almost 70 dB below the carrier due to the phase lock loop. Still closer to the carrier, within the Rabi pedestal, we see spurs mainly at 50 Hz and 100 Hz and multiples thereof. These are 70 dB or more below the carrier and thus the fractional frequency shift induced by them should be well below 1×10^{-16} [7].

B. Phase Noise

Residual SSB phase noise of the synthesizer chain was measured at 9.6 GHz using two independent synthesis chains phase locked to a common 5 MHz quartz oscillator. The measurements were made with the 9.6 GHz outputs since at the time we did not yet have two complete DDS setups to produce the 7.368 MHz. However, it is clear that the 9.6 GHz results would be quite representative of the overall phase noise of the synthesizer output. In Fig. 3 below, the SSB phase noise at 9.6 GHz shows that at low Fourier frequencies of 1–10 Hz, the residual phase noise is at least 5 dB better than the 5 MHz Quartz oscillator (multiplied to 9.6 GHz) being used by us.

C. Phase Stability of the Synthesis Chain

- *Experimental Setup*:

As shown below in Fig. 4, we use a low noise 9.6 GHz YIG source phase locked to a 5 MHz quartz oscillator to drive three independent divider chains of the synthesizer. The 5 MHz outputs of these divider chains are given to a time domain frequency stability measurement system. The measurement system has a specified (by the manufacturer) noise floor of 1×10^{-16} at 10,000 seconds but has been found to be able to do much better.

- *Phase Stability Through the Synthesizer*

The results of the phase stability measurements are shown in Fig. 5 below between pairs of the divider chains. The stability is about 1.5×10^{-15} at 100 seconds and reaches a little over 1×10^{-17} at one day. We must, however, note with caution that the results may be somewhat contaminated by the noise floor of the measurement system. For comparison, we also show in the same diagram the measured frequency stability of CSF1 operated with the present synthesizer. Clearly, the phase stability of the divider chain of the synthesizer is not a significant source of noise in CSF1.

- *CSF1 Frequency Stability with the New Synthesizer*

The fountain CSF1 was run continuously over 5 days and during this period its frequency was measured against two H-masers, H5 and H6. The pairwise frequency stability measurements are shown in Fig. 6a. Over a time scale of below 5000 seconds, the H-masers are distinctly more stable than CSF1. However, above this time scale their stabilities are about the same level. From the pairwise frequency stabilities we have computed the individual stability of CSF1 by the three-cornered-hat technique, assuming that the three clocks are completely uncorrelated. The results are shown in Fig. 6b.

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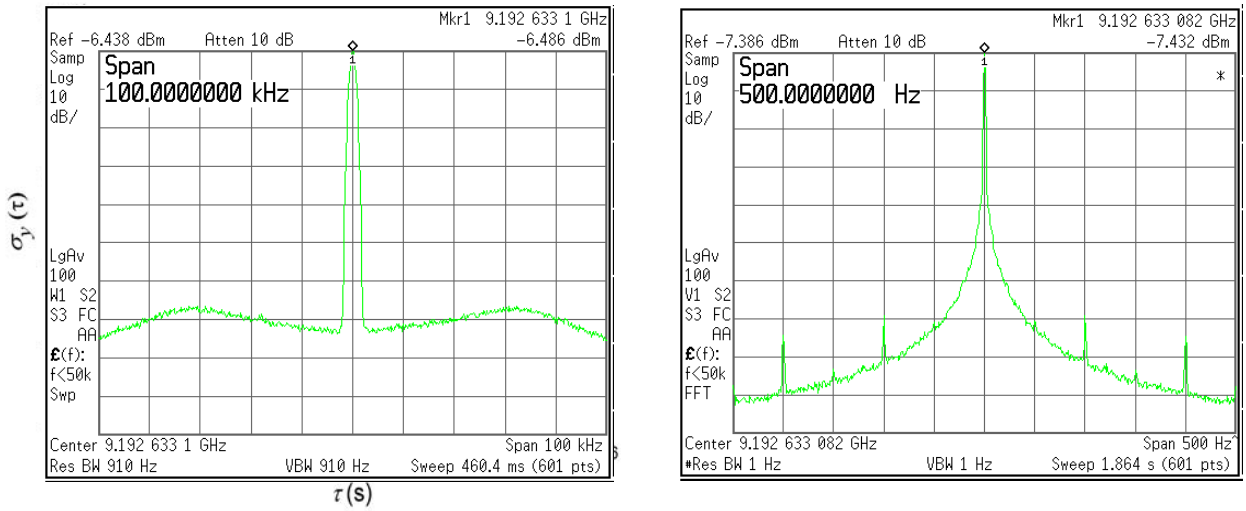

Figure 2. Frequency spectrum of the 9.192 GHz synthesizer output.

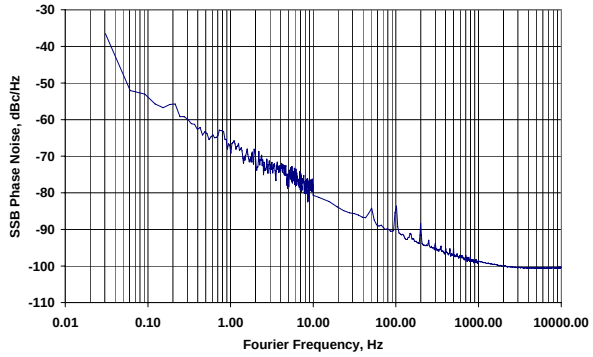

Figure 3. Residual phase noise of the divider chains of two synthesizers at 9.6 GHz

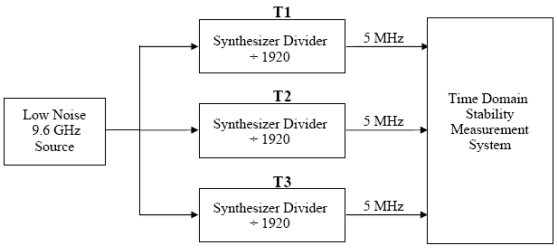

Figure 4. Pairwise stability measurements of the phase variation through the Synthesizer divider

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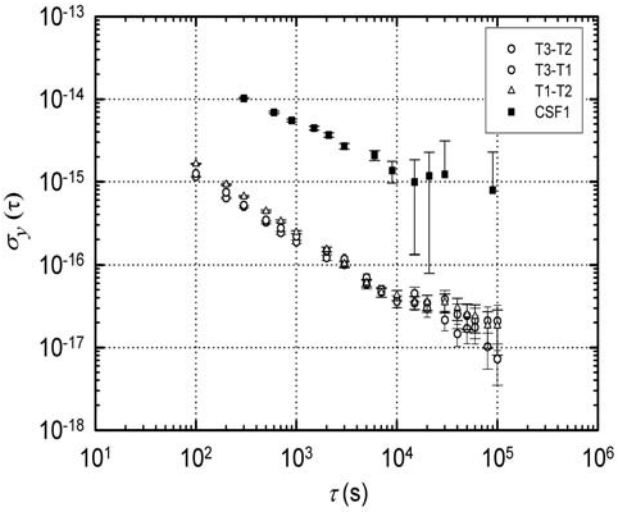

Figure 5. Pairwise stability measurements of the phase variation through the synthesizer divider

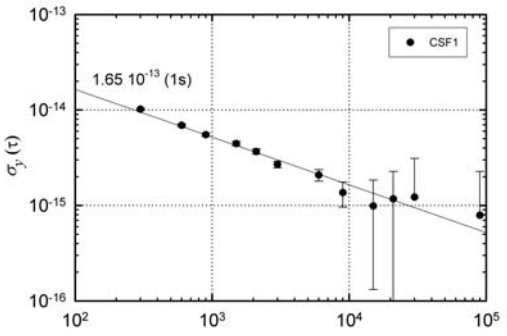

Figure 6b Frequency stability of CSF1 using the three-cornered-hat method

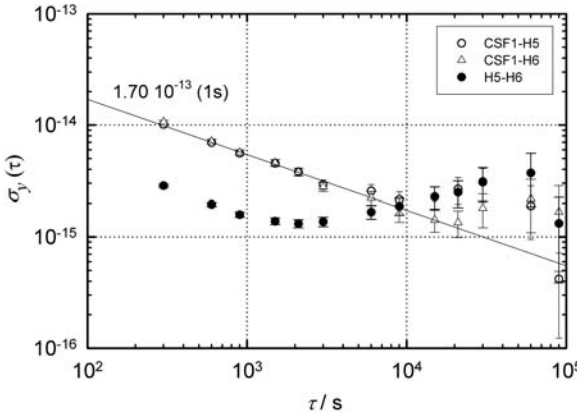

Figure 6a Pairwise frequency stability of CsF1 against the H-masers H5 and H6