Application high-speed digital-to-analog converters for direct digital synthesis of high-frequency radio signals

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Abstract. The main features of high-speed digital-to-analog converters designed for direct digital synthesis of radio frequency signals in the UHF and microwave ranges are presented. A block diagram of a digital signal generator based on high-speed DACs is proposed. These DACs are designed to create digital signal generators that work based on the direct digital synthesis method. The main specialized modes of operation of high-speed digital-to-analog converters that allow efficient use of extra components of the spectrum are studied. Images of the main frequency of synthesis occur when the signal is restored from digital to analog form. Special operating modes of high-speed DACs allow you to create broadband and ultra-wideband signals. The use of high-speed digital-to-analog converters in special modes of operation makes it possible to simplify the block diagrams of digital signal generator. The scheme is simplified by reducing the number of cascades of the output frequency multipliers.

1. Introduction

Modern telecommunications and radar systems contain digital frequency synthesizers. They are built either on the basis of a direct digital synthesis method (direct digital synthesizers, DDS) [1, 2], a digital indirect method (pulsed phase-locked frequency system, PLL), or combinations of these methods that implement hybrid frequency synthesis.

When the entire set of output waves determined by the frequency grid of the synthesizer is formed using a single reference low-noise source, this synthesis is called coherent. A reference low-noise source is usually called a reference frequency generator (Ref). Coherent synthesis is very important for advanced radar systems, broadband radio access systems, and communications. They implement a method of space-time channel separation based on digital antenna arrays (CAR) [3, 4]. One of the most important directions of development of this field of science and technology is to increase the output frequency of coherent synthesis. Increasing the operating frequency of synthesizers in such systems allows you to increase the bandwidth of the transmitted signal, thereby increasing the amount and speed of data transmission, reduce the time of the probing pulse in radar systems, and much more.

The development of microelectronics has made it possible to create high-speed digital-to-analog converters that allow forming high-frequency signals from a single carrier, as well as signals with complex modulation methods directly in the UHF and microwave bands. This paper examines the features of these synthesizers, as well as the possibility of forming high-frequency signals using high-speed digital-to-analog converters [5], operating in special synthesis modes to increase the efficiency of using secondary high-frequency components of the output signal spectrum. These components are
called images (copies of the spectrum) of the main frequency and are formed as a result of the sampling effect.

2. The general block diagram of a digital signal generator based on high-speed DACs

There is a disadvantage of widely distributed integrated DDS: the main frequency of the generated oscillation does not exceed 45% of the clock frequency and is currently 1400-1600 MHz [6]. To solve this problem, copies of the output signal spectrum are used – images of the main frequency [7]:

\[ f_{\text{img}} = |nf_{\text{clk}} + f_{\text{DDS}}|, \]  

where \( n = \pm 1, \pm 2, \pm 3, \ldots \) – number of image. If \( n = 0 \), then the main frequency \( f_{\text{DDS}} \) is filtered at the output signal of the DDS in first Nyquist’s zone.

When images are used, it is necessary to take into account the decrease in the harmonic level of the output signal spectrum. This problem is partially solved by using a DAC built on the basis of high-speed specialized DACs and FPGAs as a computing unit [8, 9].

The general block diagram of a digital high-frequency signal generator built on the basis of high-speed DACs is a direct digital synthesizer. Only this synthesizer is not made in a single integrated design, but is divided into high-performance computing blocks (figure 1).

![Figure 1. The general block diagram of a digital signal generator.](image)

To create a clock signal with the frequency \( f_{\text{clk}} \) of a digital signal generator, a reference frequency generator is used, the frequency \( f_{\text{Ref}} \) of which is multiplied by a separate frequency multiplier on transistor stages or a PLL systems. The synthesized high-frequency signal is allocated by a bandpass filter, and its frequency is multiplied by the output frequency multiplier.

High-speed digital-to-analog converter is the most important element in this digital high-frequency signal generator. Special modes of high-speed DACs allow efficient use of the output signal at image frequencies.

3. Special modes of high-speed DACs

The main feature that allows high-speed digital-to-analog converters to efficiently generate high-frequency signals is the introduction of a four-switch architecture for controlling the current source of each of the DAC reference bits (figure 2) [10].

Most common digital-to-analog converters use a two-switch architecture that allows you to connect and disconnect the current source of each of the bits to the DAC output for the full time of one clock period.
The use of four field-effect transistors allows switching at least twice in a single period, during the rise and fall of the front and back edges of the clock pulse.

Let's consider the main modes of operation of a high-speed digital-to-analog converter, which is part of a direct digital synthesizer. Each mode of operation corresponds to a specific algorithm for switching transistors.

- **Normal operation mode**, or non-return-to-zero (NRZ). The frequency response of the DAC in NRZ mode is shown in figure 3. The maximum frequency response falls in the first Nyquist zone. When using images located in other Nyquist zones, keep in mind that the frequency response envelope of the type \((\sin x)/x\) causes a decrease in the amplitude.

- **Return-to-zero (RZ)** mode. \([10-12]\). The advantage of the RZ mode is that the image harmonic amplitude increases with \(n=-1\) in the second Nyquist zone.

- **Radio frequency (RF) or mix** mode is a fundamentally different operating mode used in some high-speed DACs \([12-14]\). In its implementation, each clock pulse of the NRZ mode is represented by two different-polar pulses of duration \(\tau = T/2\) (figure 4, c). The RF radio frequency mode is optimal for operation at a high output frequency, in the second and third Nyquist zones.
By reducing the duration of the multipolar pulses of the RF mode relative to the moment \( t = 0 \), as shown in figure 4,d, the developers implement another mode of operation of high-speed DACs, known as RFZ (radio frequency return-to-zero mode) [11-13].

Another mode of operation of the DAC, conventionally called RFZ2 [16]. In it, the duration of different-polar pulses, as in the RFZ mode, is \( \tau<\frac{T}{2} \), but their duration is changed relative to the moments of time \( t=0 \) and \( t=T/2 \) (figure 4, e).

The frequency characteristics of the described high-speed DACS for various modes of operation and the harmonics of the main frequency images are shown in figure 5.

**Figure 4.** The form of clock pulses in various operating modes of high-speed DACS: NRZ(a), RZ(b), RF(c), RFZ(d), RFZ2 (e).

**Figure 5.** The frequency characteristics of high-speed DACS for various modes of operation.

The frequency characteristics of a high-speed digital-to-analog converter using special operating modes clearly show changes in the amplitudes of the spectrum components – both the fundamental frequency harmonic and its images. The normal NRZ mode, where the frequency response envelope decreases in accordance with the law \( \sin(x)/x \), is effective only for the main frequency band located in the first Nyquist's zone. RZ mode, and especially RF mode, allow you to effectively use odd images, such as \( n = -1, 1, -3, 3 \), and so on.

The increase in the amplitude of the harmonics of the image through the use of special regimes leads to a lower noise/signal and reduces power spectral density of the phase noise, as high-speed...
converter and digital driver in General. The coefficients that characterize the reduction of the phase noise level relative to the NRZ mode were obtained in [14].

4. Conclusion
A special feature of the high-speed DAC is the use of copies of the spectrum (images) of the main synthesized frequency to create broadband and ultra-broadband signals.

Using different DAC operating modes allows you to increase the signal-to-noise ratio without using additional devices by changing the frequency envelope. As a result, the phase noise characteristics of direct digital synthesizers built on high-speed DACs are improved.

For even images, it is necessary to conduct additional research and determine the most effective form of the clock pulse and the algorithm for switching the transistors of the output stage of each DAC discharge.

The high-speed DAC is able to continuously switch the operating mode during operation. This allows for the widest possible bandwidth of the synthesized signal.

The use of high-speed digital-to-analog converters in special modes of operation makes it possible to simplify the block diagrams of digital signal generator. The scheme is simplified by reducing the number of cascades of the output frequency multipliers. This allows you to increase the output frequency of the digital synthesizer.

Direct digital coherent synthesis allows you to obtain signals with complex types of modulation for telecommunications, radar and remote sensing systems. The high-speed DAC is able to continuously switch operating modes during operation. This allows for the widest possible bandwidth of the synthesized signal.

5. References.
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