Development of technology of high-speed digital-to-analogue converters to improve the efficiency of direct digital synthesis of radio-frequency signals

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Abstract. The importance of high-speed digital-to-analogue converters for the synthesis of high-frequency coherent signals is shown. A review of the main specialized modes of operation of high-speed digital-to-analogue converters is carried out, which make it possible to effectively use the side components of the spectrum that arose during the restoration of a signal from digital to analogue form. An RF2 reconstruction mode with a modified bipolar pulse sequence is proposed, which makes it possible to increase the amplitude of the images in the eighth and ninth Nyquist zones.

1. Introduction
Modern telecommunication systems, radar and navigation systems contain frequency synthesizers. There are several ways to build digital frequency synthesizers. The main ones are: synthesis based on the direct digital method (direct digital synthesizers, DDS) [1-2], digital indirect (pulse phase-locked loop, PLL), and combinations of these methods that implement hybrid frequency synthesis.

One of the most important directions in the development of this field of science and technology is to increase the output frequency of coherent synthesis. Coherent synthesis is very important for advanced radio systems that implement the method of space-time channel separation based on digital antenna arrays (DAA) [3]. Thanks to direct digital synthesizers, it became possible to digitally synthesize broadband and ultra-wideband signals [4].

The traditional way of increasing the output frequency, for example, using a mixer and a dither generator to convert the frequency upward, cannot be used, since the coherence of the synthesis is disturbed [5]. Therefore, there is a problem of increasing the signal frequency directly at the output of a direct digital synthesizer.

One of the solutions to this problem is the development of high-speed digital-to-analogue converters capable of increasing the efficiency of using images of the fundamental frequency - side high-frequency components of the spectrum of the DAC output signal [6], arising in the process of signal recovery from digital to analogue.

The development of microelectronics has made it possible to create high-speed digital-to-analogue converters. Synthesizers based on DAC data can generate signals from units of hertz to several tens of GHz. Serially produced high-speed DACs have a maximum clock frequency of 12 GHz [7, 8, 9].
The considered DACs potentially have a wide range of applications, from cellular stations and radar systems to specialized electronics used in artificial intelligence and machine learning systems [10, 11], acoustics [12].

In this paper, we review the special modes of high-speed digital-to-analog converters with various recovery pulse shapes to study the possibility of generating high-frequency radio signals.

2. Review of special modes of operation of high-speed DACs
Let’s consider the features of the usual and special modes of operation of high-frequency high-speed digital-to-analogue converters.

2.1. Normal DAC operation (no-return-to-zero, NRZ)
This mode is the traditional mode of operation for digital-to-analogue converters. During one cycle of the clock signal, the same output signal level is maintained, determined by the digital code and the reference current or voltage sources connected to the output. On the next clock cycle, the rising edge switches to another digital code value, updated at the digital input of the DAC. There is no return to zero between reconstruction pulses. An example of a signal spectrum for normal NRZ operation in the time and frequency domain is shown in figure 1.

![Figure 1. Envelope of spectrum of the DAC output signal in NRZ mode and images of the fundamental frequency.](image)

In the frequency domain, the spectrum of the reconstructed signal at the DAC output in NRZ mode is a set of harmonics. One of them, located in the first Nyquist zone, is called the fundamental frequency, and the rest, located in the higher Nyquist zones, are called fundamental frequency images. Images located in odd zones, for example, in the 3rd, 5th, etc. are called positive, and even negative. Numbers of images are designated in accordance with the nearest multiple of the clock signal frequency [6].

Using images instead of the fundamental harmonic allows you to increase the frequency of the generated signal. However, their amplitude is limited by the frequency response of the DAC. Therefore, one of the main challenges in developing new high frequency DACs is to change the frequency response of the DAC to increase the amplitude of the harmonics of the images. To achieve this goal, work is underway to create special DAC operating modes that differ from the NRZ mode by a different shape of the reconstruction pulses.

2.2. High-speed DAC architecture.
Shaping reconstruction pulses that are more complex than NRZ mode requires a redesign of the DAC output stage architecture. The two-switch architecture is traditional, when the current output of each of
the DAC bits is connected with two switches to the power supply and ground. This structure allows you to connect and disconnect the current source of each of the digits to the DAC output for the full time of one clock cycle.

To provide a return to zero (RZ) mode [13], when half of the clock cycle at the DAC output is reconstruction pulse, and in the second half the DAC output is disconnected from the source of the discharge current and connected to ground, in [14] a circuit with additional transistors is developed, shown in figure 2.

![Figure 2](image)

**Figure 2.** a) Using two additional transistors for RZ mode; b) four-switch transistor architecture for controlling the current source for each of the converter bits.

The introduction of a four-key architecture to control the current source for each of the DAC reference bits (figure 2, b) allowed high-speed digital-to-analogue converters to efficiently generate high-frequency signals in the second and third Nyquist zones when using the RF mode [15].

### 2.3. DAC operating mode with return-to-zero (RZ)
For the first time, the RZ high-frequency DAC operation mode with return to zero to change the spectrum of the DAC output signal and increase its efficiency was described in article [13].

The envelope of spectrum of the DAC output signal in RZ mode is also represented by the \((\sin x)/x\) function, but the zeros of the function are located at multiples of \(2f_{CLK}\). Some of the signal energy is lost during the synthesis process. To reduce the integral and differential nonlinearity of the RZ mode, its modification was developed in [16], called DRRZ - digital random return-to-zero.

The RZ mode can be used to synthesize wideband signals in the first or second Nyquist zones, as it flattens the envelope of the output signal spectrum.

### 2.4. DAC mode using bipolar pulses (RF)
RF mode using bipolar pulses allows to increase the efficiency of the fundamental frequency images at \(n = -1, 1\) in the second and third Nyquist zones. This mode was first described and studied in article [15] under the name two phase 1 / 2Ts. There is another variation of the special RF mode, shown in figure 3 [15], with different positive and negative pulse durations (1 / 4Ts). This allows to align the envelope in the regions of zeros of the \((\sin x)/x\) function.

The four-key DAC output stage architecture shown in figure 2 is used to generate bipolar pulses in one clock cycle. Modern high-speed DACs support RZ and RF (1 / 2Ts) modes as their main modes of operation due to their ease of implementation. These DACs include Analog Devices AD9739, AD9161, AD9162, AD9163, AD9164 microcircuits.
2.5. **DAC modes with bipolar return to zero (RFZ, RFZ2)**
Reducing the bipolar pulse duration for RF mode creates a new RFZ mode [7]. As shown in figure 3, this mode changes the envelope so that the region of the first zero of the \((\sin x)/x\) function is near \(4f_s\).

Changing the sequence of pulses made it possible to create a new regime, conventionally named RFZ2 in [17]. The shape of the spectrum envelope in this mode is similar to the envelope for the RF mode, only the width of the regions with zero value is reduced.

2.6. **DAC mode of operation using a sequence of two pulses with return to zero (DTIRZ)**
Research conducted to reduce the phenomenon of intersymbol interference (ISI) has led to the creation of a mode of operation for high-speed DACs called DTIRZ [18]. The difference between this mode and the RZ mode is that the main pulse of the RZ mode is split into two, with intervals after each pulse equal to 1/8 of the sampling period \(T_s\).

![Figure 3](image1)

**Figure 3.** Reconstruction modes NRZ, RZ, RF, RFZ and RFZ2 and their output spectrum envelopes.

3. **Proposed DAC (RF2) mode of operation using two bipolar pulses**
In this paper, it is proposed to use a new high-speed DAC mode under the code name RF2. Figure 4 shows the waveform of the reconstruction pulses and the spectrum of the DAC signal.

The sampling period time is divided into eight parts. The duration of the reconstruction pulses and the intervals between them is equal to 1/8 \(T_s\).

![Figure 4](image2)

**Figure 4.** RF2 Reconstruction Mode 2.
As can be seen from the spectrum in figure 4, the amplitude of the -4 harmonic of the image (the eighth Nyquist zone) reaches a value of +1 dB.

4. Conclusions
The considered basic modes of operation of high-speed digital-to-analogue converters RZ, RF, RFZ allow changing the amplitude of the spectrum envelope and increasing the efficiency of using the fundamental frequency images. These modes are already implemented in modern high-speed DACs from Analog Devices. The development of high-frequency integrated microelectronics allows to hope that for other new modes, as well as the RF2 mode proposed in this article, in the future there will be a possibility of implementation as part of integrated high-speed digital-to-analogue converters and digital synthesizers based on them. In addition, at present, it seems relevant to conduct research on the possibility of using high-speed DACs in special modes of operation in hybrid frequency synthesizers based on direct and indirect synthesis [19, 20].

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