Direct Digital Signal Generation for Microwave and Millimeter-Wave Radar Systems

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Abstract—Direct digital synthesizers provide broadband and flexible signal generation. Hence, they are well suited for radar applications. In this paper, we consider the EUVIS DS872 device that has a bandwidth of 3GHz and an internal memory. The goal of this work is to evaluate its usability in frequency modulated continuous wave (FMCW) radar systems. An experimental test environment has been created, where phase noise and linearity measurements have been performed. A final study considers the amplitude and phase transition after the frequency content of the signal has changed.

Index Terms— Signal generators, Direct digital synthesis, Digital-to-frequency converters, Microwave generation, Microwave devices, Millimeter wave radars.

I. INTRODUCTION

The detection performance of radar systems depend amongst others on the quality of the transmitted signal in terms of bandwidth, phase noise and linearity. In order to improve the performance of radar systems, direct digital synthesis techniques can be used. Basically, there are three ways to realize direct digital signal generation. A first and straightforward way is to use an accumulator shown in Figure 1 which counts up a digital frequency word (FCW). This results in a digital sawtooth signal that is transformed to a triangular signal by forming the complement and taking the absolute value by logic gates. This signal is then transformed to an analog signal by means of a linear digital-to-analog converter (DAC). By using different filters, as described in [1], this signal can be changed into a pure sinusoidal signal. Another strategy to obtain the sinusoidal signal is to use a pair of bipolar transistors [2].

Moreover, a DDS can be realized by using a non-linear DAC as shown in Figure 2. For this purpose, an accumulator adds the frequency word by itself and combines the result with the value of the previous addition. The resulting digital sawtooth signal is converted directly to a pure sinusoidal signal by means of a non-linear DAC [3],[4].

This has the advantages that no additional filters or transistors have to be used. However, it is difficult to design such a nonlinear DAC in practice and their power consumption is often far beyond that of a linear DAC.

The most common method for directly generating a digital signal is to employ an internal memory that contains the amplitude values of a sine. This approach is used in the present work by means of the EUVIS DS872 device. The goal is to investigate the ability of this device to generate the transmitter signal of frequency-modulated continuous wave (FMCW) radar systems.

The remainder of the paper is organized as follows. The beginning of section II compares signal generation techniques of a voltage-controlled oscillator (VCO) with DDS signal generation. After that, technical properties of the DS872 device are briefly discussed. At the end of this section, two candidate applications are described that benefit from DDS signal generation. Section III presents the experimental results in terms of linearity and phase noise behavior. Moreover, the transition between two frequency steps are evaluated.

II. DIRECT DIGITAL SIGNAL GENERATION

A. Comparison between VCO and DDS

VCOs are being used to generate linear frequency-modulated signals for FMCW-radar systems. They are suited for applications in phase locked loops (PLLs) to improve the stability of oscillators. Based on analog electronic circuitry a voltage proportional frequency can be adjusted steplessly. The result is a low noise oscillating signal.

DDS on the other hand, combines the advantages of low noise PLL oscillators with the fast and tunable ability of broadband VCOs. A DDS provides discrete and equidistant frequencies for a given frequency word. Hence, DDS devices are less sensitive against instabilities coming from fluctuations of the control voltages and currents. The frequency step size and hence the output frequency depend on the resolution, e.g. 32 bit, and the clock frequency. The higher the clock frequency for a given resolution, the larger
Figure 3: Principle of Direct Digital Synthesis with ROM and linear DAC to generate a frequency signal that is proportional to the input frequency word (FCW)

is the corresponding frequency step size. An example is given by a 3GHz bandwidth and a resolution of 32bit. This leads to a frequency step of approximately 0.7Hz. A small frequency step size is important for radar systems where frequency multipliers are used for upconversion. Hence, the frequency step size is multiplied by the same multiplication factor. Phase noise is directly coupled to both, fluctuations of the timing accuracy and jitter effects of the clock signal.

As mentioned before, DDS techniques can be realized with the aid of an adder and a digital-to-analog converter (DAC). However, more complex techniques require additional memory as shown in Figure 3. This allows not only pure sinusoidal signals but also signals of arbitrary shape. In the same manner as in the DDS without internal memory, a frequency word (FCW) is added with an adder and written to a result register. Each digital value generated in one clock cycle, the phase word, takes over the task of providing a function argument that is passed in a next step to a second memory (ROM). A table produces the corresponding phase value which is then converted by a DAC to a voltage value.

Furthermore, Figure 3 illustrates the principle of recursively adding a binary number $a$. The function value of iteration $n+1$ is given by $x_{n+1} = x_n + a$. Plotting the values against the number of additions in Figure 4 results in a linear relationship where the graph has a slope of $a$. Since the maximum number is limited by the binary width, only finite numbers can be calculated. The value must therefore be reset to zero as soon as this maximum is reached. This is done automatically in the technical implementation at the overflow of the result register.

Figure 4: Illustration of the sawtooth signal as the result of the recursive addition and overflow of the result register

The following simulation compares the echo signals that can be theoretically generated by DDS and VCO, respectively. The DDS provides a large bandwidth that covers the whole frequency range from DC to 1.5GHz. On the other hand, a typical VCO provides bandwidths of around 300MHz. For a reasonable comparison the frequency range for the VCO is defined between 1.2 and 1.5GHz. In order to transform the signals into the millimeter-wave regime a two stage multiplication is performed using x12- and x6-multipliers. Figure 5 shows the simulated matched filter responses that represent the interaction with a point target at a round-trip distance of 2m. In both cases a perfect linear modulation is assumed without any jitter effects. It can be concluded from Figure 5 that the larger bandwidth of the DDS signal results in a significantly higher range resolution. In imaging radars, the larger bandwidth leads to higher image quality.

B. Circuit Design

The EUVIS DS872 shown in Figure 6 is an integrated circuit for direct digital synthesis for output frequencies up to 1.5GHz (for the first Nyquist-Band). The DS872 uses a 32-Bit frequency-word (FCW), a 13-Bit lookup-table and an 11-Bit linear DAC to generate signals from DC up to half clock frequency. Due to the synchronization of all in-build components, the FCW can be read in via 32 separate TTL-inputs and the generated signal can be changed without discontinuities in phase and amplitude between two output-signals. EUVIS’s DS872 provides normal-hold mode and return-to-zero mode for both outputs to increase the bandwidth up to the 3rd Nyquist-Band.

Figure 6: Housing of the EUVIS DS872 with the dimensions of 1cm x 1cm

For the experimental studies a custom evaluation board has been designed. Different measurement setups have been realized during the experimental evaluation process, while only few results are shown in this paper.
C. Candidate Applications

In this section, two candidate applications are introduced where the agile signal generation of the proposed DDS can be used with great benefits, namely microwave breast cancer detection and millimeter wave radar systems.

The goal of microwave mammography in the frequency range between 0.1 and 10GHz is to detect malignant breast tissue at an early stage [6]. Therefore, the dielectric contrast between healthy and cancerous tissue is exploited. Here, ultra-wideband systems transmit a broadband signal into the dielectric medium. By means of delay-and-sum imaging the position of the tumor becomes visible. A large bandwidth of the excitation signal is beneficial to improve the 3D-image reconstructions and to enhance the probability of tumor identification. Ongoing research aims at a direct digital signal generation up to 10GHz so that frequency multiplication is not needed anymore.

The second candidate approach is Multiple-Input-Multiple-Output radar systems that operate at millimeter-wave frequencies, e.g. body or luggage scanners [5]. In order to realize a parallel transmission and reception of all antenna elements, quasi-orthogonal or noise waveforms are being sent by each transmitter. In this application, DDS improves the performance of signal generation by means of arbitrary waveform generators (AWG). Currently, we are working on a DDS-unit that supports AWG-functionalities.

III. Experimental Results

A. Phase noise measurements

The phase noise is measured with the measurement setup shown in Figure 7. Digital frequency words are selected manually and the frequency responses are measured with a HP8593 spectrum analyzer. As the clock source we used a Rohde&Schwarz SMS2 and a HP8671B frequency generator.

Figure 8 presents the course of the phase noise at 750MHz output frequency. The clock frequency is 3GHz. The phase noise at a distance >30 kHz from the carrier is less than -100dBc/Hz. It can be shown that the phase noise without DDS is approximately -100dBc/Hz, too. This leads to the conclusion that the DDS device does not significantly influence the phase noise level. The major contributions come from the 3GHz clock signal.

B. Linearity Considerations

The linear adjustment of the DDS was evaluated since it has a direct impact on the resulting echo signals and the image quality of FMCW-radar systems. Figure 9 illustrates the linearity plot between adjusted and measured frequencies in the frequency range between 500MHz and 600MHz. The linearity is clearly visible.

C. Instantaneous change of signal frequency

Finally, Figure 10 shows the transition after changing the value of the frequency word and hence the output frequency of the signal. It can be observed that no abrupt amplitude and phase jumps occur.
CONCLUSIONS

In this paper, we investigated direct digital synthesis techniques for radar applications by means of the EUVIS DS872 device. Experimental studies have been performed that revealed a low phase noise of less than -100dBc/Hz at a distance >30 kHz from the carrier. Moreover, a linear frequency characteristic was measured that is important for FMCW-radar systems. A final study considered the amplitude and phase transition after the frequency has changed. An almost perfect transition without jumps was observed.

Future works aim at arbitrary waveform generation of frequencies up to 10GHz. This is the typical frequency range commonly used for microwave breast cancer detection.

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REFERENCES