An Ultra-Wide Band Orthogonal Digital Signal Generator

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Abstract: Three methods of generating waveform digitally are introduced at first. The time-domain and frequency-domain representations of sine wave at the output of a waveform generator are carried out. Then some special problems and the solutions associated with ultra-high speed system design are given. An ultra-wide-band orthogonal signal generator, whose sampling rate can reach 250MSPS, is described. The system employs data multiplexing architecture to decrease the speed of memories. Test results show that the waveform generator has an excellent performance. The phase balance between two branches being less than 5 degrees, the SFDR being larger than 70dBc, phase noise being lower than -100dBc/Hz at 1kHz offset can be reached when sine wave is generated.

Key words: waveform generator, propagation delay, reflection, crosstalk, transmission line

1. Introduction

Nowadays, wide-band digital communication systems and other applications increase the demand for the generation of ultra-wide band orthogonal signal digitally. Basically, there are three techniques for the digital generation of an orthogonal signal [5].

The first one is based on DSP, which computes the waveform sample values and sends them to a digital-to-analog converter. The later converts the sample data to an analog waveform. This is typically slow compared to the others but is the simplest one.

Direct digital synthesizers (DDSs) digitally generate a stepped sine wave at an output frequency \( f_o \) from a clock frequency \( f_c \). It has the advantage of being able to synthesize high spectral purity sine wave signals over a wide range of frequencies and with excellent frequency resolution utilizing compact digital integrated circuits. But it is not flexible enough to synthesize complex waveforms.

The waveform generator, which reads data from previously written random access memory (RAM) and converts them to analog waveforms, is widely used in test equipment for radar and communications applications because of its flexibility. It can generate some complex signals and waveforms just by writing corresponding data to RAM.

2. Analysis of the Digital Sine Wave Generation

Contents within the waveform generator are two sources of distortion. One is due to the finite wordlength of the quantization, the other is due to the non-ideal transient of DACs. For the waveform generator, finite quantization of the signal samples can lead to signal impairments. A complex-sine output from the generator can be represented by

\[
\begin{align*}
    s(t) &= \sum_{n=-\infty}^{\infty} \left[ 2^{n-1} \cdot \exp \left( j2\pi f_0 \cdot nT_c \right) + e(n) \right] \cdot \delta(t - nT_c) \cdot h(t) \\
    &= s_i(t) + j \cdot s_q(t) + e(t)
\end{align*}
\]

where,

\( s_i(t) \) is the clock frequency and \( T_c = \frac{1}{f_c} \);
\( h(t) = 1 \) for \( 0 \leq t < T_c \);
\( s_i(t) \) and \( s_q(t) \) are in-phase and quadrature branch output respectively, and
\( e(t) \) is noise only portion resulted from finite quantization of the signal samples.

The spectrum of the complex-sine output of the generator is
\[ S(f) = \sum_{n=\infty}^{2^{D-2}} \left[ 2^{D-2} \cdot \delta(f - f_0 - nf_c) \cdot \sin\left( \frac{\pi f}{f_c} \right) e^{-j\pi n f_c} \right] + E(f) \]

where \( E(f) \) is the impurity spectral component resulted from \( e(t) \).

The \( e(t) \) is in principle random error quantities which results in the errors being uniformly distributed from \(-\)LSB/2 to LSB/2 for a complex waveform. In this case \( e(t) \) can be taken to be statistically independent and uniformly distributed, the resulting noise spectrum contributes equal amounts of AM and PM noise at the output. And the spectral density can then be written as \(^2\)

\[ E_f(f) = \frac{\sigma^2}{f_c^2} \left| \frac{\sin(\pi f f_c)}{\pi f f_c} \right|^2 \]

for \( 0 \leq f < f_c \), where \( \sigma^2 = \text{LSB}^2 / 12 \). So the carrier-to-noise ratio at the output of the waveform generator is given by

\[ \frac{C}{N_o} = 10 \log \left( \frac{\left( \frac{2^{D-2}}{2} \cdot \frac{f_c}{\sigma^2} \right)}{\frac{f_c}{\sigma^2}} \right) = (1.76 + 6.02 D + 10 \log f_c) \text{ dB c/Hz} \]

In the general spurious case, the same total amount of noise energy is distributed between fewer discrete spectral lines. Worst case, the quantization errors can lead to a sinusoidal component of peak value LSB/2. In this case the spurious level is given by

\[ S_f = -20 \log 2^D \text{ dBc} \]

The non-ideal transient of DACs, which are modeled by the zero-order-hold waveform conventionally, degrades spectral performance, especially when the clock speed is increased to the extent that the transient rise and fall times are a significant part of the clock period. In this case the output spectral purity is decided mainly by the DAC’s dynamic specifications such as glitch area, setting time, rise and fall times. The slower fractional-order-hold DAC can improve the spectral purity performance of waveform generator remarkably \(^3\).

3. Ultra-high Speed Circuits Design and Implementation

3.1 Problems of the Ultra-high Speed Circuits Design and Implementation

To generate ultra-wide-band signals, ECL devices that can work at a speed about several hundred megahertz are needed. Different from middle or low speed systems, there are some special problems involved in the high-speed system \(^4\).

(1) Propagation delay

In the ultra-high speed circuits, propagation delay is comparable to the period of the signals. Precise control and prediction of timing is crucial to proper operation. So it is important to analyze and control propagation delay in pivotal timing applications such as data bus, address bus, clock lines and some important control lines.

(2) Crosstalk

Crosstalk refers simply to disturbance on one signal line due to signals on neighboring lines. The value of crosstalk can be described as following equation \(^5\):

\[ U_N = \frac{U_S}{1 + R_e / R_p} \]

where:

\( U_N \) is the crosstalk value on the signal line,

\( U_S \) is the magnitude of the signal propagating on the adjacent line,

\( R_e \) is the inter-impedance between the transmitting lines,

\( R_p = \sqrt{L_e / C_e} \), and \( L_0 \) and \( C_0 \) are the inductance and the capacitance per unit length of the transmission line respectively.

(3) Reflection

A signal propagating down the line is partially reflected back to the source if the line is not terminated correctly in its characteristic impedance. When the reflected signal arrives at the source, it is re-
reflected back toward the load. The reflected signal continues to be re-reflected by the source and load impedance and is attenuated with each passage over the transmission line. The output response appears as a damped oscillation. Reflection adds extra delay and meanwhile can result in logic wrong when over/undershoot crosses the threshold.

(4) Analog and Mixed-signal circuits

In the waveform generator, analog and mixed-circuits, which are sensitive to interference, are used. The digital noise will be coupled to the analog and mixed parts and degrade its performance badly if it is not designed carefully.

3.2 Solutions to the problems of the Ultra-high Speed Circuits Design and Implementation

(1) Propagation delay

The edge rates of the ECL family are such that most interconnects must be treated as transmission lines. Thus a controlled impedance environment is necessary to produce predictable interconnect delays as well as limiting the reflection phenomena of undershoot and overshoot. Propagation delay \( T_{pd} \) per unit length of the transmission line can be expressed as

\[
T_{pd} = \sqrt{L_0 \cdot C_0}
\]

(7)

(2) Reflection

To minimize the potential hazards associated with reflections on transmission lines, three basic termination techniques are available: Minimizing the unterminated line length, series termination and Parallel termination [6].

a) Minimizing Unterminated Line Length

An unterminated transmission line is also referred as a stub or an open line. The maximum length of an unterminated transmission line is determined by equation

\[
L_{max} = t_r / (2 \cdot T_{pd})
\]

(8)

where,

\( t_r \) is rise time of the signal.

If a transmission line whose length is larger than \( L_{max} \), it must be terminated.

b) Series Termination

Series damping is a technique in which a termination resistance, \( R_{ST} \), is placed between the driver and the transmission line with no termination resistance placed at the receiving end of the line. Where the following equation is required:

\[
R_{ST} + R_O = Z_O
\]

(9)

Here \( R_O \) is the output impedance of the driver. Series termination techniques are useful when the interconnect lengths are long or impedance discontinuities exist on the line. Additionally, the signal traveling down the line is at half amplitude.

c) Parallel Termination

When the fastest circuit performance or the ability to drive distributed loads is desired, parallel termination is the method of choice. An important feature of the parallel termination scheme is the undistorted waveform along the full length of the line. A parallel termination line is one in which the receiving end is terminated to a voltage \( V_{TTR} \) through a resistor \( R_T \) with a value equal to the line characteristic impedance, i.e. \( R_T = Z_0 \). For 50 \( \Omega \) systems, the typical value of \( V_{TTR} \) is -2V.

(3) Crosstalk

Crosstalk is a kind of pulse noise and is not eliminable. But some measures can be taken to lessen the impairment of crosstalk:

a) Decrease the magnitude of the transmitting signal. In this manner, Series Termination is a relative good choice.

b) Increase the distance between two signal lines;

c) Decrease the length of a pair of parallel lines.

(4) Analog and mixed circuits

Maintaining a low impedance large area ground plane is important to practically all analog circuits today, especially at high speeds [7]. The ground plane not only acts as a low impedance return path for high frequency currents but also minimizes EMI/RFI emissions. In mixed parts, the analog and digital ground planes should be separated and connected to a common system “star” ground, which generally locates at the power supplies. In order to decrease the
noise introduced to the analog ground by digital parts, the digital and analog ground can be connected through a ferrite bead. The amplifiers are sensitive analog devices whose ground pins should be connected analog ground plane. And DACs should be treated as analog devices and their ground pins should be connected to analog ground plane, whether a pin is an analog ground pin or a digital ground one.

4. A Practical 250MSPS Orthogonal Signal Waveform Generator

Figure 1 shows the block diagram of a practical 250MSPS orthogonal signal waveform generator where DAC can work at a maximum update rate of 250 MSPS for each branch.

PC computes the waveform samples data and sends them to MCU. The MCU (TMS320C50), which controls the start and stop of the generator, is the control center of the entire system. Data are stored in MCU’s memory and post-processed by MCU to meet the DAC’s format. The post-processed data are then transferred to I-branch and Q-branch respectively and converted to orthogonal analog waveform.

In order to meet the demand for the speed of DACs, the system employs data multiplexing architecture to enable each branch to access four memory units and read out four data at one time. At the outputs an ultra-high speed multiplex is used to select the desired data. Thus the speed of memories is only one-fourth of the DAC’s update rate. To ensure two branches’ outputs to be orthogonal, it is essential to uniform the characteristic of the two branches. The timing of all the crucial signal lines is controlled precisely. Besides, LPF and Ultra-wide band OPA, which play an important role in the performance of the system, must be designed carefully to ensure phase and amplitude balance between two branches.

Besides complex-sine signal, the waveform generator can used to generate any kinds of complex signals, for example, radar echo and wide-band noise, etc.

![Figure 1 Block Diagram of a 250MSPS Orthogonal Waveform Generator](image1)

![Figure 2 Output waveform and the spectrum of sine wave (f_0=125MHz)](image2)
5. Some Results

The waveform of a sine wave with a frequency of 125MHz at the output of the waveform generator and its spectrum are showed as figure 2. It shows that the signal has an excellent spectral purity. The SFDR is 71.433dBc. The phase noise is -100.816dBc/Hz at 1KHz offset.

When different frequency waveform is generated, the phase balances between the two branches are about 1.4 to 5 degrees, the SFDR is larger than 70dBc and the phase noise is lower than -100 dBc/Hz at 1KHz offset.

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