DDS-Based Flexible UWB Pulse Generator Using Anti-Nyquist Sampling Theorem

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Abstract. A real all-digital and all-coherent arbitrary ultra wideband pulse generator is presented. The generator is a multi-core & single-channel (MCSC) direct-digital-synthesizer (DDS) which consists of 16 sub-cores and a high speed digital analog converter AD9739. The ultra-wideband pulses are generated according to the proposed anti-Nyquist sampling theorem. Their frequencies are aliasing in the first and second Nyquist zones. By purposely aliasing the spectrum, the output bandwidth can be increased greatly. All the parameters including pulse width, bandwidth, amplitude, pulse type, pulse repeat frequency and modulation are user-controlled on-the-fly. In order to test the performance, monopole pulse, monocycle pulse and two 4th order Gaussian pulses are generated. The monopole pulse whose pulse rate can achieve 2.5 GHz has a 10% pulse width of 450 ps, a 200 mV peak amplitude and a -10 dB bandwidth of 2.15 GHz.

1. Introduction
Ultra wideband (UWB) technique is widely used in communication and radar fields. A key issue of UWB technique is the generation of UWB pulse. Conventional analog generators use fiber Bragg grating (FBG) [1] and step-recovery diode (SRD) [2] to generate UWB pulses. Conventional digital sources utilize the complementary metal-oxide-semiconductor (CMOS) integrated circuits to generate glitches [3, 4, 5, 6]. High speed DAC-based direct waveform synthesis (DWS) was first presented in [7] for UWB applications. Similar to [7], this letter contributes to provide a much more flexible and easy implementable UWB pulse source for radar and communication applications based on Direct Digital Synthesizer (DDS). The key innovation includes two parts. Firstly, the letter designs a multi-core & single-channel DDS (MCSC-DDS). This MCSC-DDS contains 16 DDS sub-cores and a high speed digital analog converter (DAC). It consists of off-the-shell commercial components. The MCSC-DDS can generate arbitrary UWB pulse compared with other generators. Some waveform distortions caused by the non-ideal characteristics of the circuit can be compensated by the MCSC-DDS. Secondly, different from [7], the MCSC-DDS does not employ high sample rate like [7] but uses the proposed anti-Nyquist sampling theorem to increase the output bandwidth and generate various UWB pulses. That is, let the frequencies in the first and second Nyquist zone overlap each other. As a result, the output bandwidth will be more than 1/2 of the sample rate, or even be equal to the sample rate. By using this method, we can increase the output bandwidth without changing any hardware or increasing the sample rate. But the anti-Nyquist rule can only be applied to UWB pulse generation.
2. Design of the MCSC-DDS

Several simple forms of MCSC-DDS architectures have been presented in literatures [8, 9, 10]. However, the theory of MCSC-DDS has not been expatiated elaborately. Consider a sampled discrete-time sine wave:

$$s(n) = a \sin(2\pi f_0 n T_s + \phi)$$  \hspace{1cm} (1)

Where $T_s$ is the sampling interval, $a$ is the amplitude, $\phi$ is the output phase and $f_0$ is the output frequency. Rewrite Eq. 1 in the form of series summation as [11]:

$$s(n) = a \sum_{m=-\infty}^{\infty} \delta(m-n) \sin(2\pi f_0 m T_s + \phi)$$  \hspace{1cm} (2)

Where $\delta(n)$ is Dirac function. Decimate Eq. 2 by $D$, and then Eq.2 can be divided into $D$ subgroups

$$s(n) = a \sum_{i=0}^{15} \sum_{m=-\infty}^{\infty} \delta(Dm + i - n)$$
$$\times \sin[2\pi f_0 T_s \cdot Dm + 2\pi f_0 T_s \cdot i + \phi]$$ \hspace{1cm} (3)

According to DDS theory, for a DDS who has an $N$-bit phase accumulator, the output frequency satisfies $f_0 = K f_s / 2^N$, where $K$ is the frequency tuning word of DDS. Therefore, Eq. 3 is rewritten as

$$s(n) = a \sum_{i=0}^{15} \sum_{m=-\infty}^{\infty} \delta[Dm + i - n] \times \sin \left[ \frac{2\pi}{2^N} (DKm + iK) + \phi \right]$$  \hspace{1cm} (4)

Equation 4 represents the basic principle of the MCSC-DDS. In Eq. 4, for each subgroup $i$, the sample rate is $f_s / D$. So it can be implemented by a low-speed DDS sub-core which performs at the speed of $f_s / D$. The exact value of $D$ is determined by the combination of FPGA and DAC. In general, $D$ is relatively small when we use a high-speed FPGA. On the other hand, $D$ is relatively large when we use a high-speed DAC. Here we set $D = 16$, then we need 16 DDS sub-cores to implement Eq. 4. For DDS sub-core $i$, the sub-core frequency tuning word is $16K$, the phase control word is $\phi$, the amplitude is $a$ and the phase offset is $iK$. A prototyping MCSC-DDS is designed according to Eq. 4.

The block diagram is shown in Fig. 1. In Fig. 1, the MCSC-DDS is RAM-based. The output waveform is determined by the content in RAM and the corresponding parameters in Eq. 4. So this MCSC-DDS is capable of generating arbitrary waveforms. For all DDS sub-cores, the RAM is equal. All the DDS sub-cores perform in parallel in FPGA. The output of each DDS sub-core is delivered to DAC through a high-speed Multiplexer in sequence at the speed of $f_s$. In general, the Multiplexer is embedded in the DAC chip.
3. Anti-Nyquist sampling theorem

In this letter, the high performance, high frequency 14-bit DAC AD9739 [12] is selected for the MCSC-DDS. Its sample rate \( f_s \) is up to 2.5 GHz. The AD9739 uses the quad-switch architecture shown in Fig. 2. In this architecture, a constant glitch at \( 2 \times f_s \) is created in the process, as shown in Fig. 3. These features are the foundation of the proposed anti-Nyquist sampling theorem. Some other commercial DAC chips, such as EV12DS130AVZPY whose sample rate is up to 3 \( GS/\)s, are suitable for the MCSC-DDS according to the practical requirement.

For UWB applications, the MCSC-DDS must try its best to increase the output bandwidth. If the MCSC-DDS cannot increase the sample rate, it looks like that the maximum output bandwidth is no more than 1.25 GHz according to Nyquist sampling theorem. But this is not the practice in some UWB applications. As mentioned above, the DAC can create a glitch at \( 2 \times f_s \) which implies that the output bandwidth can reach \( 2 \times f_s / 2 \) for UWB applications. But the total sample rate of the MCSC-DDS is \( f_s \). So the Nyquist rule is violated with respect to the MCSC-DDS. Therefore, a method called as anti-Nyquist sampling theorem is presented for UWB applications. The MCSC-DDS purposely uses the aliasing phenomenon to increase the output bandwidth by violating Nyquist sampling theorem. That is, let the frequencies in the first and second Nyquist zone be distorted by the overlapping of frequency components above and below \( f_s / 2 \) in the original signal. Using this method, the output bandwidth will be more than 1/2 of the sampling frequency or even be equal to the sampling frequency. In other words, the output bandwidth is increased without changing the sample rate of the MCSC-DDS. It is illustrated in Fig. 3. In Fig. 3, \( X'(f) \) is the aliasing spectrum, the shadowed part is the overlapping frequency components. The output bandwidth satisfies
\[ f_s' / 2 \leq f_H' - f_L' \leq f_s \]  \hspace{1cm} (5)

Where \( f_s' < f_s \) and \( f_H' - f_L' > f_H - f_L \). It means that we can obtain a wider output bandwidth with lower sample rate by using anti-Nyquist sampling theorem. This is one of the most important reasons for us to use DDS technique to generate UWB pulses. From Fig. 4 we can see that, by controlling the amplitude \( a \), the code \( s(n) \), the sample rate \( f_s \) and the operating mode of DAC [7], the MCSC-DDS can generate various UWB pulses of different bandwidth and modulation.

\[ X(f) \]

First Nyquist zone

Second Nyquist zone

(a)

\[ X(f) \]

First Nyquist zone

Second Nyquist zone

(b)

Figure 3. Output spectrum of the MCSC-DDS with (a) normal mode and (b) aliasing mode.

4. Measurement setup and results
The FPGA is Xilinx Virtex-5. The sample rate of the DAC is 2.5 GHz. The MCSC-DDS output is directly connected to the sampling equipment LeCroy Wave-master. By controlling the RAM in FPGA and other parameters, the DDS can nearly generate arbitrary UWB pulse. In this letter, two doublets, a monocycle pulse and a monopole pulse are generated. The MCSC-DDS setup [7] with respect to these waveforms are depicted in Fig.4. The measured waveforms are shown in Fig. 5, both in the frequency and time domains. From Fig. 5, we can see that their spectrums are aliasing in the first and second Nyquist zone. The monopole pulse has a 10% pulse width (PW) of 450 ps, a peak-to-peak amplitude (PPA) of 0.20 V and a -10 dB bandwidth (BW) of 2.15GHz. Its spectrum is aliasing in the first and second Nyquist zones. The monocycle pulse has a 10% PW of 0.71 ns, a PPA of 0.31 V and a -10 dB BW of 2.35 GHz. Its spectrum is also aliasing in the first and second Nyquist zones and the BW is about equal to 94% of sample rate. The first 4th order Gaussian pulse (doublet) has a PW of 0.99 ns, a PPA of 0.47 V and a -10 dB BW of 1.76 GHz which is equal to 70.4% of sample rate. The second doublet has a PW of 1.07 ns, a PPA of 0.25 V and a -10 dB BW of 1.67 GHz. Fig. 6 and Fig. 7 show the variable modulation capabilities of on-off keying (OOK), pulse position modulation (PPM)
and bi-phase at the same time. The maximum pulse rates of monopole and monocycle are 2.5 GS/s and 1.25 GS/s, respectively. These results demonstrate the high flexibility of the generator and the efficiency of the proposed anti-Nyquist rule. All measured parameters are listed and compared to the performance of prior works [1-6] in Table 1.

![Figure 4](image1.png)  
**Figure 4.** MCSC-DDS setup for (a) monopole, (b) monocycle and (c)(d) two doublets.

![Figure 5](image2.png)  
**Figure 5.** Measured waveforms in (a) time domain and (b) frequency domain.

![Figure 6](image3.png)  
**Figure 6.** Measured monopole pulses at 2.5 GHz pulse rate with OOK, PPM and bi-phase modulation.
Figure 7. Measured monocycle pulses at 1.25 GHz pulse rate with OOK and bi-phase modulation.

Table 1. All measured parameters and the different performances compared to the prior works in [1–6].

| Ref. | PW (ns) | PPA (V) | BW (GHz) | Technology  | PRF (MHz) | Type        |
|------|---------|---------|----------|-------------|-----------|-------------|
| This work | 0.46    | 0.20    | 2.15     | MCSC-DDS    | 2500      | monopole    |
| This work | 0.71    | 0.31    | 2.35     | MCSC-DDS    | 1250      | monocycle   |
| This work | 0.99    | 0.47    | 1.76     | MCSC-DDS    | 625       | doublet1    |
| This work | 1.07    | 0.25    | 1.67     | MCSC-DDS    | 500       | doublet2    |
| [1]   | 0.24    | 5.6     | 4.0      | SRD         | 10        | monopole    |
| [2]   | 0.19    | 0.02    | 9.3      | FBG         | 100       | monocycle   |
| [2]   | 0.21    | 0.02    | 10.5     | FBG         | 100       | doublet     |
| [3]   | 0.67    | 1.24    | 2.8      | CMOS        | 100       | monopole    |
| [3]   | 1.48    | 2.64    | 2.0      | CMOS        | 100       | monocycle   |
| [4]   | 1.0     | 0.24    | 2.0      | CMOS        | 100       | higher order|
| [5]   | 0.8     | 0.07    | 6.0      | CMOS        | 2500      | monocycle   |
| [6]   | 0.5     | 0.67    | 4.5      | CMOS        | 50        | higher order|

5. Conclusion
A DDS-based real all-digital flexible UWB pulse generator is presented in this letter. The generator consists of off-the-shell commercial components. According to the proposed anti-Nyquist method, a monopole pulse, monocycle pulse and two 4th order Gaussian pulses whose spectrums are aliasing are generated using the MCSC-DDS. Their -10 dB BW is more than 1/2 of the sample rate. In order to demonstrate the flexibility, their parameters, such as modulation, waveform type, are set to be different from each other. With these features, the DDS-based UWB pulse generator can offer more potential applications compared with prior work. It is expected to be useful for some radar and communication systems.

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